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Performance Characteristics of Yardney Lithium-Ion Cells For the Mars 2001 Lander Application

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ABSTRACT

NASA requires lightweight rechargeable batteries for future missions to Mars and the outer planets that are capable of operating over a wide range of temperatures, with high specific energy and energy densities. Due to the attractive performance characteristics, Lithium-ion batteries have been identified as the battery chemistry of choice for a number of future applications, including Mars Rovers[1] and Landers[2,3]. The Mars 2001 Lander (Mars Surveyor Program MSP 01) will be among one of the first missions which will utilize Lithium-ion technology. This application will require two Lithium-ion batteries, each being 28 V (eight cells), 25 Ah and 9 kg (18 kg total). In addition to the requirement of being able to supply at least 90 cycles on the surface of Mars after a 1 year storage and cruise time, the battery must be capable of operation (both charge and discharge) over a wide temperature range (–20°C to +40°C), with tolerance to non-operational excursions to –30°C and 50°C. To assess the viability of lithium-ion cells for these applications, a number of performance characterization tests have been performed on state-of-art Yardney lithium-ion cells, including: assessing the room temperature cycle life, low temperature cycle life (-20°C), rate capability as a function of temperature (-30° to 40°C), pulse capability, self-discharge and storage characteristics, as well as, mission profile capability. This paper will describe the Mars 2001 Lander mission battery requirements and will contain results of the cell testing conducted to-date in support of the mission.

INTRODUCTION

NASA is planning several missions in the near future to continue the exploration of the Mars, including some missions being aimed at retrieving Martian samples back to the Earth. Various missions, such as Landers, Rovers, Mars Ascent Vehicles (MAV) and Orbiters are thus being planned and will be supported by different advanced technologies. One advanced technology in the area of power sources is the lithium ion battery, which has been selected as the baseline for the upcoming MSP 2001 Lander, which will be fabricated by Lockheed-Martin Astronautics, in collaboration with JPL. The MSP 2001 Lander was originally scheduled for launch in April 2001, however, it has recently been delayed to an expected launch date in 2003.

The goal of the Mars 2001 mission is to complete the global reconnaissance of Mars and perform surface exploration in support of a number of science objectives. In particular, an attempt will be made to 1) globally map the elemental composition of the surface, 2) acquire spatial and spectral resolution of the surface mineralogy, 3) determine the abundance of hydrogen in the subsurface, 4) study the morphology of the Martian surface, 5) provide descent imaging of the landing site, 6) study the nature of local surface geologic processes, and 7) assess the viability of future human exploration in terms of radiation-induced risks, and soil and dust characteristics. To accomplish these objectives, the MSP 2001 Lander will incorporate a number of key technologies and experimental devices, including: 1) a Mars Descent Imager (MARDI) 2) a Mars Radiation Environment Experiment (MARIE), 3) a Mars In-Situ Propellant Production Precursor (MIPP), 4) a Mars Environmental Compatibility Assessment (MECA) experiment, 5) a Robotic Arm and Robotic Arm Camera, 6) a Stereoscopic Panoramic Imager (T=PanCam), as well as, 7) a Mini-Thermal Emission Spectrometer (Mini-TES).

After evaluating a number of different cell chemistries, supplied by different vendors responding to the Lockheed-Martin BAA, Yardney Technical Products was selected as the vendor to supply the lithium-ion batteries for the MSP01 2001 Lander. The cell chemistry adopted by Yardney to meet the projected mission requirements consists of MCMB carbon anodes, $LiNiCoO_2$ cathode materials, and a low temperature electrolyte (1.0 M $LiPF_6$ EC+DMC+DEC (1:1:1)) developed at JPL.[4,5] The cell design selected by Yardney is a prismatic arrangement, which enables easy stacking of the cells to produce an eight cell battery. It must noted that the cell and battery technology development effort was made possible, in part, by the participation of the NASA-DOD consortium recently formed to establish domestic capability to manufacture lithium-ion cells and batteries in the US.[6]

POWER SUBSYSTEM FOR MSP 01 LANDER

The main power source for the MSP 2001 Lander consists of a 300 W Ga-As solar cell array. The auxiliary power source augmenting the solar array for the nighttime operations will be a Li-ion rechargeable battery. Two lithium-ion batteries will be used with the current orientation, each being 28 V, consisting of eight cells and a capacity of 25 Ah (name plate capacity). Both batteries will be contained within a single housing, and the total battery assembly should not weigh more than 18.2 Kg. Although both batteries will be operated during the course of the mission, a single battery can fulfil the needs of the entire mission, thus, one battery can be considered as being redundant. Each of the batteries will have an independent charge-control unit, with individual cell bypass features for charge control.

Li ION CELL/BATTERY REQUIREMENTS

The mission dictates that a number of performance requirements must be met by the 28 volt, 25.0 Amp-hour batteries to successfully complete the planned mission. Perhaps the most important feature of the battery is its requirement to operate (both charge and discharge) at continuous rate of C/5 over a wide range of temperatures (-20° to +40°C) once the Lander has successfully landed on the surface of Mars. The battery should be capable of providing a minimum EOL capacity of 25 Ah. The typical discharge drains will be C/5 to a maximum of 50% DOD. However, with both the batteries being connected in parallel (with a diode protection), the actual depths of discharge could be even milder than 50%. The maximum charge current is projected to be approximately 5 A (C/5). In addition to operating efficiently on the surface of Mars, the batteries should be able to withstand 50 A pulses at 0°C for short duration, during the entry, descent and landing phase (EDL). In case that the Li-ion batteries are unable to meet this criterion, a thermal battery (Li-FeS_2) is being considered as in the case of Mars Pathfinder, however, recent testing has shown that is may not be necessary. Prior to satisfying both of these requirements, the battery must survive a pre-discharge storage duration of nearly 2 years (6 months to one year pre-cruise storage) and a one year cruise period at 0° to 30°C.

Li ION CELL/BATTERY EVALUATION

In order to assess the viability of using lithium-ion technology for the Mars 2001 Lander, a test plan was formulated by Lockheed-Martin, in collaboration with JPL and Yardney, which reflects the need for data which address the various mission requirements. The test plan generally consists of determining: (i) the room cycle life performance (25°C), (ii) low temperature cycle life performance (-20°C), (iii) discharge and charge rate capability at different temperatures (-20, 0, 25, and 40°C), (iv) pulse capability at different temperatures and different state-of-charge (SOC), (v) optimum storage condition to ensure minimal loss of performance (vi) ability to perform an EDL load profile, and (vii) ability to cycle under surface temperature profile conditions. Although testing to achieve these ends was performed by all three institutions, the results of the cell testing performed at JPL only will be considered in this paper.

CELL TESTING RESULTS

CYCLE LIFE PERFORMANCE

According to the projected mission plans, the battery should be capable of providing a minimum of 90 cycles once the spacecraft has reached the surface of Mars. Due to the fluctuating temperatures on the surface of Mars during the course of a typical sol period, the battery will be required to cycle efficiently over wide temperature variations (-20 to +40°C). In addition, successful operation must be demonstrated after being subjected to an extended cruise period (~ 11 months) and an additional storage period from the date of manufacturing and time of launch. In order to assess the viability of the lithium-ion technology to meet these requirements, a combination of tests were undertaken to establish a comprehensive data base to enable predictive performance trends. One general test performed to evaluate the life characteristics involved 100 % DOD cycling of cells between a voltage range of 3.0 Vdc to 4.1 Vdc at a number of temperatures. As illustrated in Fig. 1, 20 Ahr prototype cells have been cycled successfully cycled > 800 cycles at both ambient temperatures as well as at –20°C (charged and discharged at low temperature).

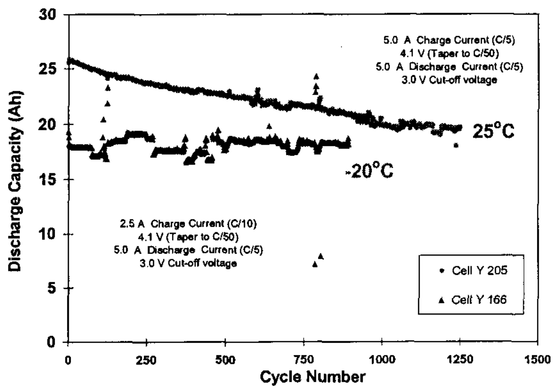

Fig.1. Cycle life performance (100% DOD) of Yardney 20 Ahr prototype lithium-ion cells at 25 and –20°C.

As illustrated by Fig 1, upon completing 750 cycles the cells cycled at room temperature delivered ~ 85% of the initial capacity, whereas, the cells cycled at –20°C were observed to deliver ~70% of the initial capacity. In addition, it is apparent that the capacity fade is much less at low temperatures compared with higher temperatures, due most likely to the increased rates of impedance build-up with increasing temperature.

CYCLING AT ALTERNATING TEMPERATURES

In addition to evaluating the cycle life performance of the cells under conditions of constant temperature, effort was focused upon determining the effect of cycling between temperature extremes for fixed number of cycles. As shown in fig. 2, cells were cycled intermittently (10 cycles) between two temperature extremes (-20°C and 40°C). As illustrated, the impact of cycling a cell intermittently at 40°C results in a dramatic decrease in amount of capacity being able to be delivered at low temperature. After completing 200 cycles under this regime, cells were observed to lose 50-75% of the initial capacity delivered at low temperature.

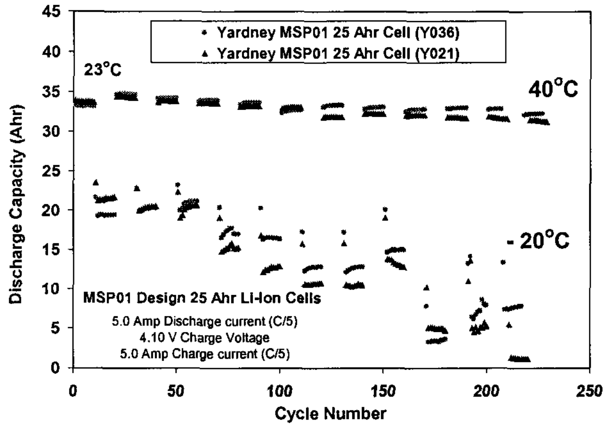

Fig. 2. Variable temperature cycling of Yardney MSP01 25 Ahr design lithium-ion cells.

This is in sharp contrast to the minimal capacity fade obtained when the cells are continually cycled at low temperature with no excursion to higher temperatures. However, it must be noted that there is little degradation of the cell performance at higher temperatures, suggesting that the observed capacity losses at low temperature are due to an increase in cell impedance, most likely due to increased passivation at the electrode surfaces resulting in resistive films preventing facile lithium ion kinetics, which is magnified at low temperatures. It must be emphasized, however, that in terms of mission requirements, this type of testing represents a worst case scenario. According to the mission profile, the cells will not experience prolonged high temperature exposure (>30°C) or prolonged low temperature exposure (>-10°C) for significant length of time, but rather will be subjected to milder conditions as discussed in the mission simulation testing section.

In an attempt to understand more fully the mechanism by which the cell impedance increases upon cycling under these conditions, a number of additional tests were performed on Yardney prototype 5 Ahr cells of similar chemistry. In these series of tests, the impact of the charge voltage upon cell degradation was investigated by either charging the cells to either 4.0 or 4.1V during the period of high temperature exposure. As illustrated in Fig. 3, the loss in performance at low temperature can be decreased by using lower charge voltages at high temperatures. One possible interpretation of these results is that oxidative decomposition of the electrolyte is accelerated at high temperatures and high charge voltage which results in the formation of increasingly resistance electrode films (both anode and cathode).

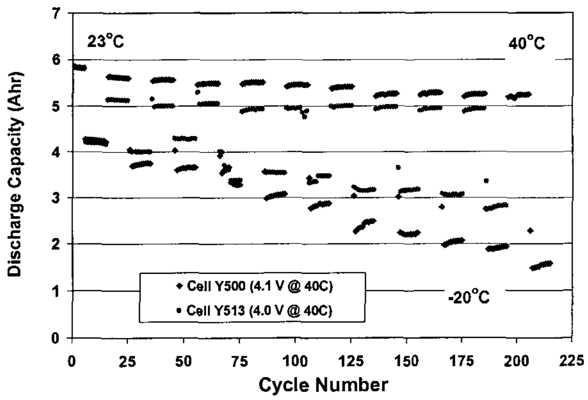

Fig. 3. Variable temperature cycling of Yardney 5 Ahr design lithium-ion cells.

This interpretation is supported, in part, by electrochemical impedance spectroscopy (EIS) measurements taken on the cells while carrying out the variable temperature testing. As shown Fig. 4, the cell which was charged at lower voltages during the high temperature cycling displayed smaller increases in cell impedance and lower film resistance.

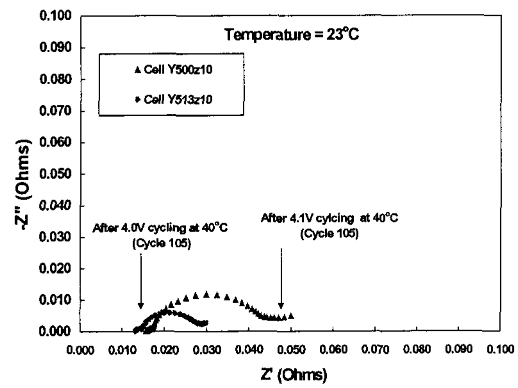

Fig. 4. EIS measurements of 5 Ahr Li-ion cells during variable temperature cycling test.

DISCHARGE PERFORMANCE AT DIFFERENT TEMPERATURES

Since demonstration of efficient performance at low temperature was a major technological challenge, a large amount of emphasis was placed upon evaluating the discharge capacity over a number of different rates (C/2, C/3, C/3.3, C/5 and C/10) and temperatures (-30, -20, 0, 23, and 40°C). When Yardney MSP01 design cells were evaluated at a C/5 discharge rate (5.0 Amp discharge to 3.0 V) at different temperatures, good performance was observed over the range of temperatures, as shown in Fig 5. At –20°C, ~ 24 Ahr of capacity was capacity was delivered (cell charged at –20°C using a C/10 charge rate to 4.1V), representing ~70% of the room temperature capacity. As shown in Fig. 6, the cells were also observed to deliver excellent specific energy over a large range of temperatures, with over 85 Wh/kg and 140 Wh/kg being delivered at –20°C and 40°C, respectively.

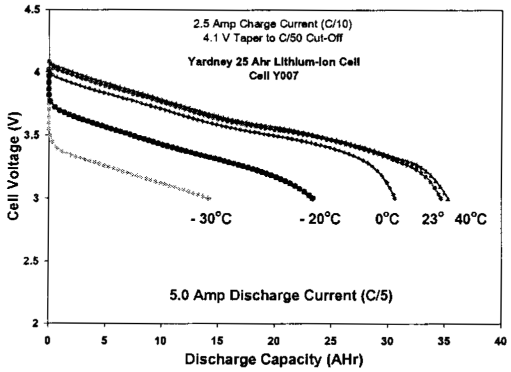

Fig. 5. Discharge capacity of a Yardney MSP01 design 25 Ahr cell at a C/5 discharge rate and at different temperatures (-30, -20, 0 , 25 and 40°C).

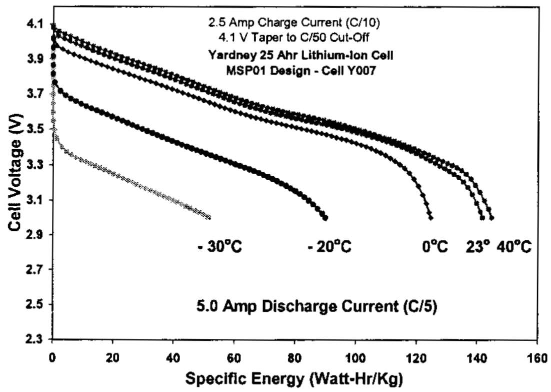

Fig. 6. Specific energy of a Yardney MSP01 design 25 Ahr cell at a C/5 discharge rate and at different temperatures (-30, -20, 0 , 25 and 40°C).

In the course of the discharge rate characterization studies, it was observed that better low temperature performance was generally obtained when the relative tests were performed sequentially from low temperatures to high temperature (-30, -20, 0, 23, and 40°C), rather than in the reverse order (40, 23, 0, -20, and –30°C). This trend underscores the sensitivity of the low temperature performance depending upon cell history and extent of exposure at high temperatures. The most dramatic illustration of this behavior was observed when cells were exposed to +50°C cycling (8 cycles). As shown in Fig .7, significant loss in low temperature capability was observed when the cells were evaluated at –20°C before and after the high temperature (+50°C) cycling.

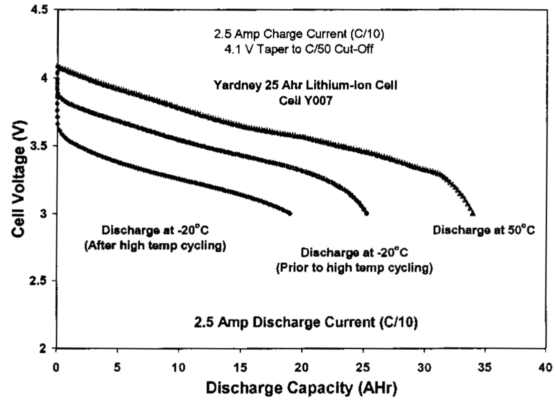

Fig. 7. Impact of high temperature cycling upon the low temperature performance of a Yardney MSP01 design 25 Ahr cell (C/5 discharge to 3.0V).

CHARGE CHARACTERISTICS AT DIFFERENT TEMPERATURES

In the same manner in which the discharge capacity as a function of temperature was evaluated, the charge characteristics were assessed at different rates and temperatures. As shown in Fig. 8, cells displayed good charge acceptance over a wide temperature range (-30° to 40°C) with ~70% and ~50% of the ambient temperature capacity realized at –20°C and –30°C, respectively.

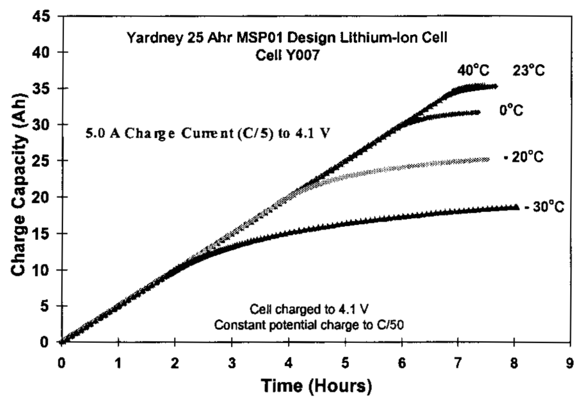

Fig. 8. Charge capacity of a Yardney MSP01 design 25 Ahr cell at a C/5 charge rate to 4.1V and a C/50 taper current cut-off as a function of temperature.

As shown in Fig. 9, essentially full capacity can be obtained in ~ 4 hours with high charge rates (C/2=12.5 Amps) at –20°C, with little variation in charge capacity as a function of constant current charge rate.

This is primarily due to the fact that the charge characterization tests were performed with a constant potential charging step with the same taper current cut-off value in common (C/50=0.500 Amps).

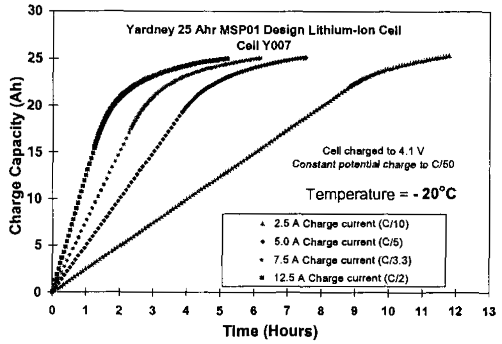

Fig. 9. Charge capacity of a Yardney MSP01 design 25 Ahr cell at –20°C at different rates (constant current charge to 4.1V with a C/50 taper current cut-off).

A general trend consistently observed throughout the charge characterization tests is that upon going to lower temperatures more significant amounts of the total charge capacity accepted by the cells occurred in the constant potential charging mode, as illustrated in Fig. 10, due to inability to sustain high charge current densities without large electrode polarization.

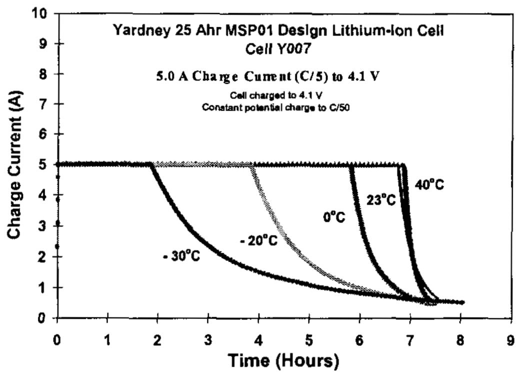

Fig. 10. Applied charge current as a function of temperature (-30, -20, 0 , 25 and 40°C) with a C/5 charge rate (5 Amps) to 4.1V and a C/50 taper current cut-off).

Although the bulk of the charge rate characterization tests were performed using a taper current cut-off value to end the constant potential charging mode, such that charge step is terminated when the current decays to less than 0.500 Amps (C/50), some characterization was performed using extended charge periods. This is especially relevant for the 2001 Lander application, since the battery will be permanently connected to the buss and will experience longer charge periods. These conditions generally lead to more capacity accepted, especially at low temperature, as illustrated in Fig. 11.

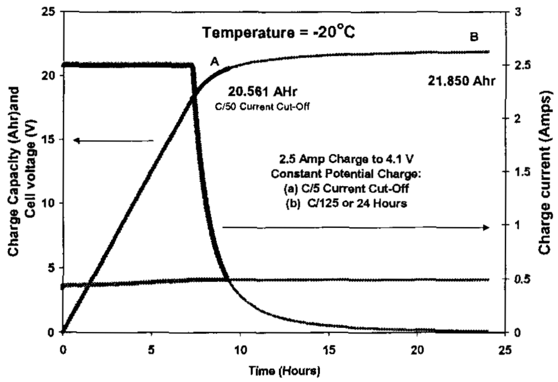

Fig. 11. Charge characteristics of a Yardney 20 Ahr prototype cell at -20°C with extended constant potential charging.

One initial concern with operating the batteries under such conditions, with very long charge periods, is that an increased rate of cell degradation was anticipated due to the length of time the cells are held at high potential (for the reasons mentioned previously). For this reason, cells were cycled (100% DOD) using especially long charge periods (24 hours) and compared with cycling results obtained when the charge period is discontinued upon reaching a taper current cut-off value of C/50 (~ 6 hour charge time with C/5 charge rate to 4.1 V). However, no significant increase in the capacity fade characteristics was observed when an extended charge period was employed, as shown in Fig. 12.

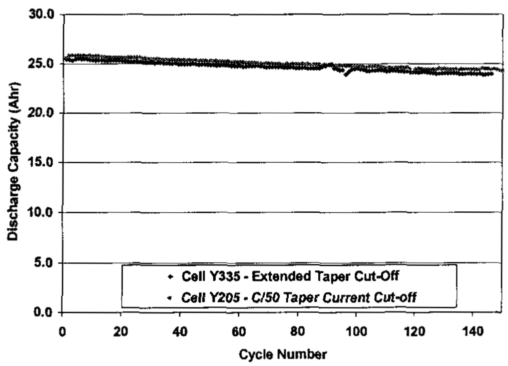

Fig. 12. Cycle life performance of Yardney 20 Ahr prototype cells using different charge regimes.

STORAGE CHARACTERISTICS

In order to assess the capability of the technology to meet the various life requirements, it was necessary to conduct a number of tests to evaluate the effect of prolonged storage upon performance. In the case of the Mars 2001 Lander, the battery must be operational after an 11-month cruise period while the spacecraft is in transit to Mars. The first set of tests were aimed at determining the effect of storage temperature and cell state of charge upon performance when the cells are stored under open circuit conditions (OCV). The cells selected for this testing were of an early generation, 20Ah capacity design. In order to represent the extremes projected for the cruise storage period, two different temperatures were selected (0 and 40°C) and two different states-of-charge (50 and 100%) were utilized. For these initial tests, the cells were: (i) first cycled (5-10 cycles) prior to storage (ii) stored at the selected temperature and state-of-charge (iii) discharged to 3.0V to determine the residual capacity and (iv) then cycled a number of times (5-10 cycles) to determine the extent of permanent capacity loss of the cells (if any) as a result of the storage period. The cells were first subjected to a two month storage period accompanied by full performance characterization before and after, followed by a longer ten month storage period. As shown in Table 1, in general minimal permanent capacity loss was observed over the range of conditions investigated, with the largest loss in capacity with the cells which were stored at high temperature (+40°C). However, if the cells are stored at low temperature (0°C) and low state-of-charge over 96% of the initial capacity is realized after one year of cell storage.

	Two Month Storage Period				Ten Month Storage Period			Total
Storage Condition	Initial Capacity	Capacity Prior To Storage (Ah)	Capacity After Storage (Ah) 5th Disch.	Rever. Capacity (%)	Capacity Prior To Storage (Ah)	Capacity After Storage (Ah) 5th Disch.	Rever. Capacity (%)	Total Reversible Capacity After 12 Month Storage
(0°C and 50 % SOC)	27.879	27.609	27.327	98.98	26.972	26.786	99.31	96.08
(40°C and 50 % SOC)	28.749	28.021	27.479	98.07	27.918	25.595	91.68	89.03
(0°C and 100 % SOC)	25.475	25.471	24.781	97.29	24.607	24.296	98.74	95.37
(40°C and 100 % SOC)	25.674	25.670	25.156	98.00	23.912	22.727	95.05	88.52

Table 1. Discharge capacity of Yardney 20 Ahr prototype cells before and after being subjected to various storage conditions (OCV storage).

In addition to determining the impact of storage conditions upon the reversible capacity at ambient temperature, the cells were also characterized at low temperature (-20°C). In general, the storage of the cells was observed to affect the low temperature capability more dramatically, and proportionately lower capacities were observed as illustrated in Table 2. In contrast to the trend observed when the cells were evaluated at room temperature, the effect of state-of-charge was seen to be more dominant than the effect of temperature upon in determining the low temperature capability. The best results were obtained with cell which was stored at 50% SOC and at 0°C, with ~66% of the room temperature capacity realized at –20°C (compared to ~ 70 % of the room temperature being delivered prior to the storage characterization tests.

		Ten Month Storage				Low Temperature Performance	
Storage Condition	Initial Capacity	Capacity Prior To Storage (Ah)	Capacity After Storage (Ah) 5th Discharge	Rever. Capacity (%)	Total Reversible Capacity (% of Initial)	1st Discharge at -20°C (5 Amps = C/5)	% of Initial Capacity
(0°C and 50 % SOC)	27.879	26.972	26.786	99.31	96.08	17.276	61.97
(40°C and 50 % SOC)	28.749	27.918	25.595	91.68	89.03	18.935	65.86
(0°C and 100 % SOC)	25.475	24.607	24.296	98.74	95.37	12.995	51.01
(40°C and 100 % SOC)	25.674	23.912	22.727	95.05	88.52	11.400	44.40

Table 2. Low temperature performance (-20°C) of Yardney 20 Ahr prototype cells before and after being subjected to various storage conditions (OCV storage).

In addition to investigating the effect of storage under OCV conditions, effort has been devoted to evaluating the viability of storing the cells connected to the buss for the duration of the storage period. This is especially relevant due to the fact that the spacecraft design is simplified if the cells are connected to the buss for the duration of the mission. In order to simulate potential cruise conditions, a number of cells (4) were stored for ~11 months connected to the buss and stored at 10°C. The cells were float charged at 3.875 V which corresponds to ~70% SOC. Similar to the methodology described for the previous storage study, all cells were characterized in terms of the reversible capacity before and after storage at various temperatures. As shown in Table 3., excellent reversible capacity was obtained after 11 months of storage under these conditions, with less that 5% permanent capacity loss observed in all cases.

	Storage After 20 Days				Storage After 11 Months			
Last Discharge Prior to Storage (Ahr)	1st Discharge After Storage (Ahr) 23°C	2nd Discharge After Storage (Ahr) 23°C	% of Initial Capacity (Reversible Capacity)	Permanent Capacity Loss (%)	1st Discharge After Storage (Ahr) 23°C	2nd Discharge After Storage (Ahr) 23°C	% of Initial Capacity (Reversible Capacity)	Permanent Capacity Loss (%)
33.804	26.034	33.523	99.169	0.831	25.6252	32.9636	97.515	2.485
33.962	25.959	33.534	98.738	1.262	29.059	32.266	95.006	4.994
34.153	25.445	32.788	96.005	3.995	25.639	32.999	96.622	3.378
33.727	25.922	33.460	99.210	0.790	25.478	32.917	97.599	2.401

Table 3. Discharge capacity of Yardney MSP01 design 25 Ahr cells before and after being subjected to storage (cells stored at 10°C and 70% SOC).

When the low temperature performance was assessed following the 11 month storage period, less cell to cell variation in performance was observed with cells stored at 10°C and 70% SOC on the buss compared with the group of cells stored under various OCV conditions. The consistency of the values obtained is encouraging when considering potential battery issues related to how well the cells are matching in capacity and performance characteristics throughout the mission life. Only 5-10% reduction in capacity was observed at –20°C after prolonged storage connected to the buss, as illustrated in Table 4.

		Storage After 11 Months				Low Temperature Performance After Storage Period			
	Last Discharge Prior to Storage (Ahr)	1st Discharge After Storage (Ahr) 23°C	2nd Discharge After Storage (Ahr) 23°C	% of Initial Capacity (Reversible Capacity)	Permanent Capacity Loss (%)	1st Discharge (Ahr) -20°C	% of Initial Room Temp Capacity	2nd Discharge (Ahr) -20°C	% of Initial Room Temp Capacity
Y018	33.804	25.62524	32.9636	97.515	2.485	22.466	66.46	19.537	57.79
Y031	33.962	29.059	32.266	95.006	4.994	22.099	65.07	19.437	57.23
Y043	34.153	25.639	32.999	96.622	3.378	22.224	65.07	19.299	56.51
Y054	33.727	25.478	32.917	97.599	2.401	22.397	66.41	19.647	58.25

Table 4. Low temperature performance of Yardney MSP01 design 25 Ahr cells before and after being subjected to storage (cells stored at 10°C and 70% SOC).

Overall, the results indicate that efficient storage of lithium-ion cells can be achieved while connected to the buss if proper conditions are selected. As illustrated in Fig. 13, when the discharge profiles are compared before and after storage, very little change in performance is observed, with minimal degradation of operating voltage and minimal capacity loss (~ 2.5%).

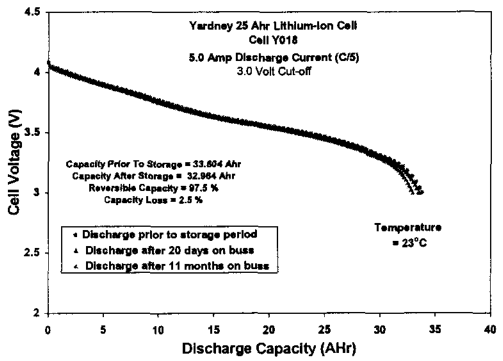

Fig. 13. Discharge capacity of a Yardney MSP01 design 20 before and after storage on the buss at 10°C (70% SOC) for 11 months.

EDL PROFILE

After completing the cruise period, the battery is expected to assist in the entry, descent, and landing process, which involves supplying power to various pyros and landing functions. The general load profile that the battery will experience during this period is shown in Fig. 14. The most demanding segment of the load profile consists of a 20 Amp discharge current onto which 30 Amp pulses are applied, thus, both contributing to produce 50 Amp loads (2C discharge rate) for short duration (100 milliseconds). In terms of mission requirements, the ability to sustain cell voltages above 3.0 V throughout the duration of this test at 0°C is the most difficult to fulfill.

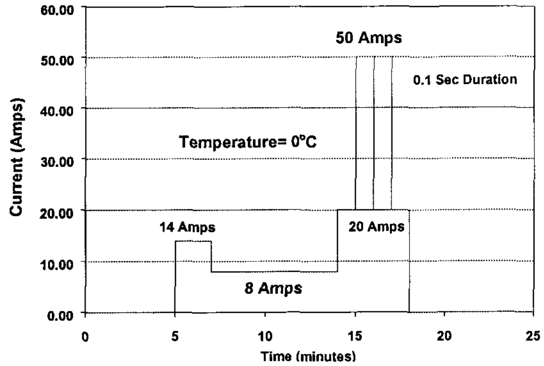

Fig. 14. Load profile of the Lander battery during the entry, descent, and landing process.

Since performance data relating to the EDL load profile is more relevant on cells which have been subjected to prolonged storage to simulate the cruise phase of the mission, the tests were performed on the group of cells previously described which were stored under OCV conditions. Due to the variation in cell performance observed after the differing storage conditions, some variation in cell polarization was expected when subjected to the high current loads. This indeed was the case, with the cells which were subjected to conditions of high state of charge displaying the greatest cell polarization and the inability to sustain a voltage greater that 3.0 V during the high current (50 Amp) pulses. In contrast, the cells stored at low state-of-charge were able to maintain much higher operating voltages throughout the duration of the load profile, never dipping lower than 3.2 V, as shown in Fig. 15. Again it should be noted that these cells were of an earlier generation, 20Ah capacity design and thus not designed to meet these pulse requirements.

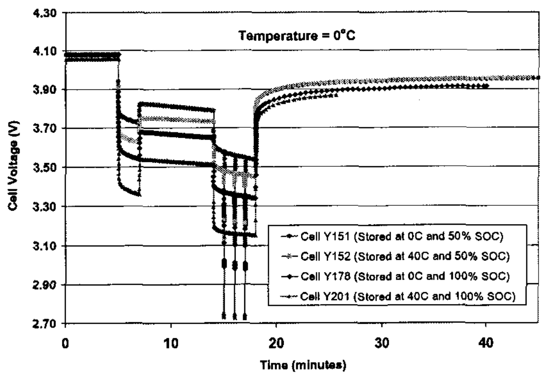

Fig. 15. EDL profile of Yardney 20 Ahr prototype cells after being subjected to ~ 1 year OCV storage.

Similar to the trends discussed earlier in relation to the low temperature capabilities, the state-of-charge during storage appears to have more influence upon the pulse capability compared to temperature of storage.

In addition to the group of cells which were stored under OCV conditions, the MSP01 design cells which were stored on the buss for 11 months were also subjected to the EDL profile. As shown in Fig. 16, excellent results were obtained being capable of successfully meeting the mission objectives, with the operating voltages never dipping below 3.4 V throughout the load profile.

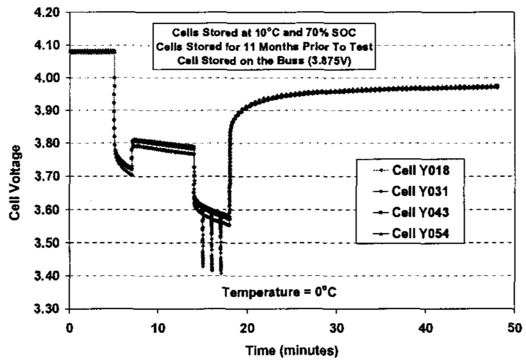

Fig. 16. EDL profile of Yardney MSP01 25 Ahr cells after being subjected to11 months storage connected to the buss.

In addition, very consistent data was obtained for the four cells studied, which were stored under identical conditions (10°C, 70% SOC = 3.875 V) prior to the pulsing test.

MISSION SIMULATION PROFILE

Once the spacecraft has landed on the surface of Mars, the battery is expected to cycle successfully for a minimum of 90 sols, with the desire of successfully completing at least 200 cycles. According to the current estimates of the Martian surface temperature profile, and the corresponding temperature swings that will be experienced within the Lander thermal enclosure, the battery will be expected to operate over a large range of temperatures (Δ 60°C). In order to simulate the battery operation over the course of the entire mission, a number of temperature ranges were investigated which correlate to the projected battery environment as the Martian season begins to change. These ranges are characterized by the widest temperature swings experienced in the beginning of the mission, and less severe, but colder temperature ranges later in the mission. Thus, continuous cycling was performed under the following conditions: (a) 20 cycles (days) over a temperature range of –20°C to 40°C, (b) 10 cycles at –20°C to 30°C, (c) 10 cycles at –20°C to 20°C, and a (d) 100 cycles at –20°C to 10°C. The electrical profile during this cycling consists of charging the cells with a constant current (C/5 rate) to 4.1V for a total charge time of 12 hrs, and a relatively mild discharge current (1 Amp or C/25 rate) for a total of 12 hrs, corresponding to 12 Ahr of capacity (~40% DOD). As shown in Fig. 17 for a typical mission simulation cycle, the beginning of the charge period occurs when the battery experiences the coldest temperatures, whereas, the beginning of the discharge period commences when the highest temperatures are experienced.

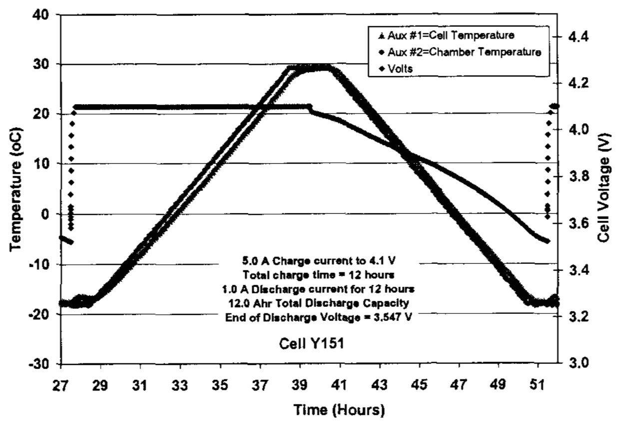

Fig. 17. Typical mission simulation cycle displaying the cell voltage response and temperature profile.

Due to the fact that a fixed amount of capacity is discharged each cycle (12 Ahr), the performance characteristics of the mission simulation cycling is most adequately expressed in terms of the end-of-discharge voltage. The end of life for the cells subjected to this test has been designated as being when the cells drop below 3.0 V upon discharge. As illustrated in Fig. 18, when prototype 20 Ahr cells were cycled under these conditions, successful completion of over 40 cycles has been observed over a number of different temperature ranges as previously described. These cells had previously been subjected to a 12 month OCV storage and EDL pulsing (described earlier) prior to the mission simulation testing. Thus, the observed cell performance is especially relevant, since the cell histories prior to the mission simulation profile testing reflect similar conditions to that expected to be experienced by the actual Lander battery. The fact that the operating cell voltages never dip below is 3.4 V, and display little capacity fade, is encouraging in terms of meeting the mission requirement previously described. Even more relevant mission simulation testing data is currently being generated on the MSP01 design cells which were previously stored on the buss at 10°C (70% SOC), which more adequately represents the actual projected storage conditions.

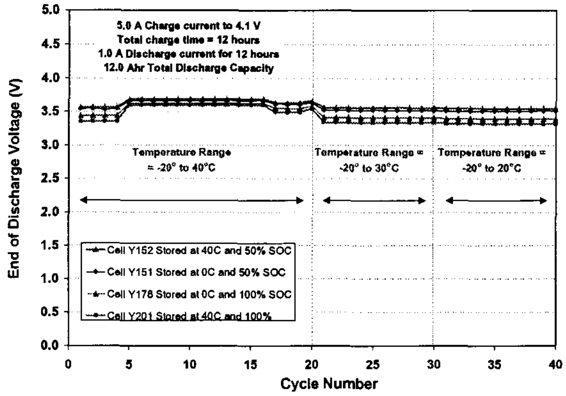

Fig. 18. Mission simulation cycling of prototype 20 Ahr lithium-ion cells.

CONCLUSIONS

A number of Yardney prototype 20 Ahr size and MSP01 design 25 Ahr size lithium-ion cells have been evaluated to determine their viability for use in the upcoming Mars Lander mission. This was accomplished by implementing a number of general and mission specific performance tests, including room temperature cycle life, low temperature cycle life (-20°C), rate capability as a function of temperature (-30° to 40°C), storage characteristics, pulse capability, as well as, mission profile cycling capability. When evaluating the cycle life performance, the technology has been demonstrated to well exceed the mission requirements of 200 cycles over a wide rage of temperatures (-20 to 40°C). Some diminishment in low temperature performance, however, was observed if the cells were cycled to extensively at higher temperatures (40°C). Good discharge and charge rate capability for the cells was demonstrated over a wide range of temperatures (-30° to 50°C), with greater than 24 Ahr being delivered at –20°C with at a C/5 rate (charge and discharge at low temperature). Thus, the performance of the cells was demonstrated to meet the low temperature requirements established for the mission. The results from a number of storage tests that were performed indicate that the least amount of cell degradation occurs when the cells are stored at low temperatures and low state-of-charge. In addition, it was demonstrated that float charging the cells at a fixed voltage (storage on the buss) is a viable method of storage and results in minimal performance degradation. Provided that the cells are stored under desirable conditions for the long cruise period, the load profile of the entry, descent, and landing phase can be effectively sustained, including 50 A pulses for short duration. When the cells were subjected to the mission simulation cycle life testing, which mimics the conditions the battery will experience on the surface of Mars, all of the cells cycled successfully. These results were obtained on cells which were previously subjected to both extended storage periods and the EDL load profile. In summary, it has been demonstrated that Yardney lithium-ion cells have met the performance requirements of the MSP01 Lander.

ACKNOWLEDGEMENT

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, for the MSP 01 Lander Battery program and Code S Battery Program under contract with the National Aeronautics and Space Administration (NASA).

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Performance Characteristics of Yardney Lithium-Ion Cells for the Mars 2001 Lander Application

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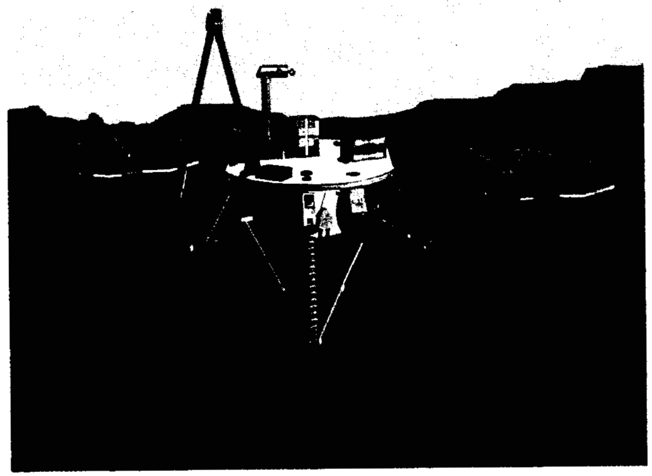
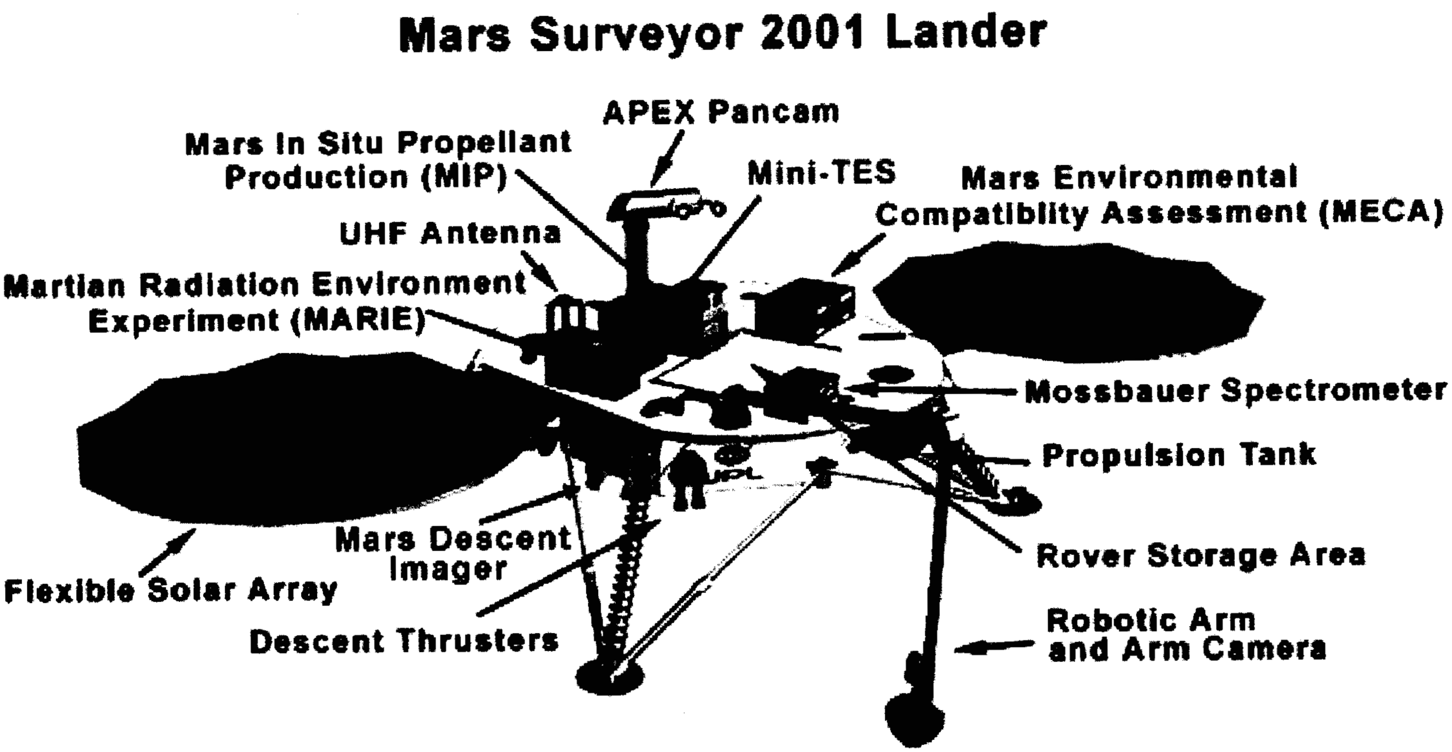
Las Vegas, Nevada
July 23-27, 2000

Mars Surveyor 2001 Lander

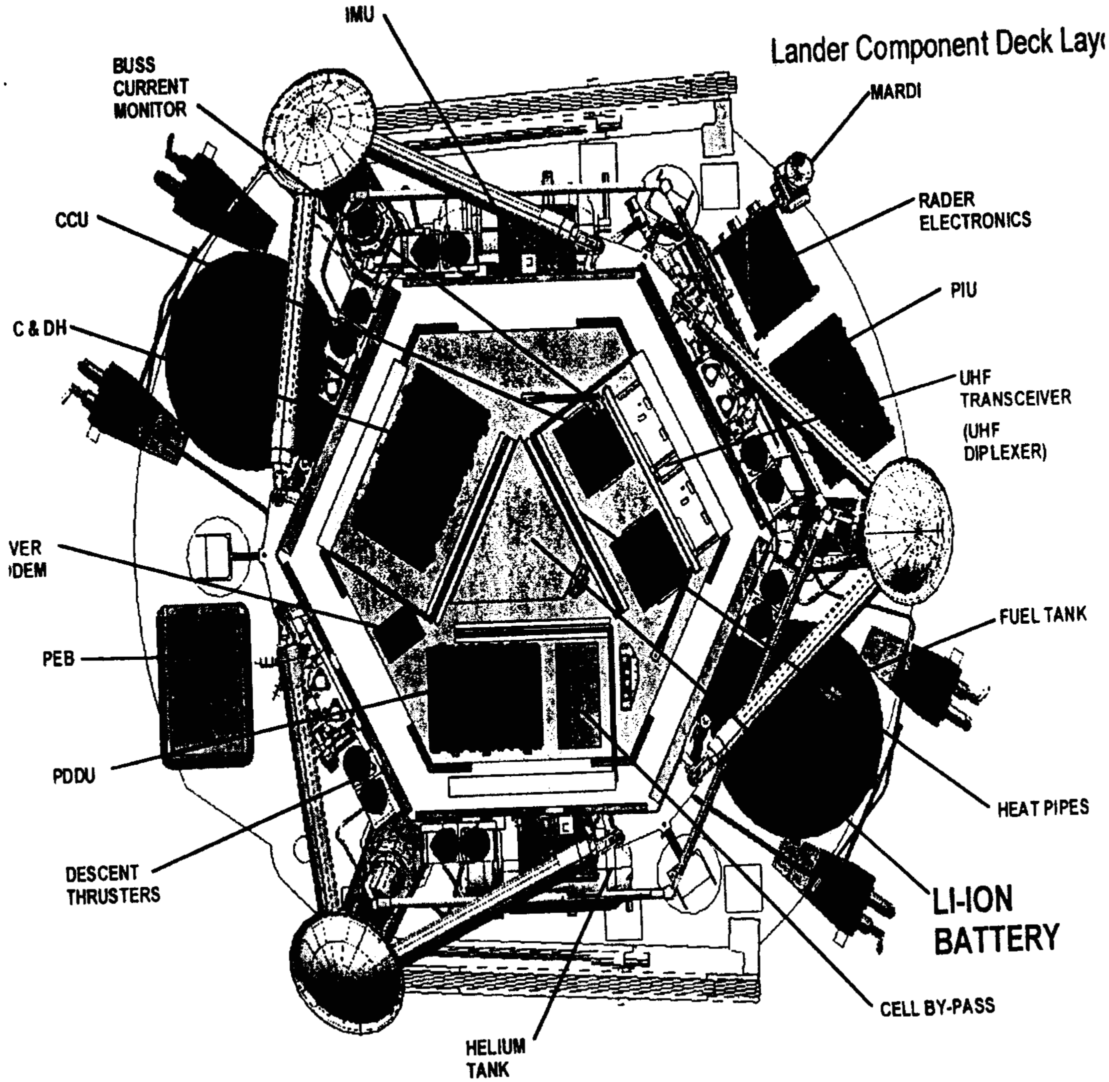
- Mission originally scheduled to launch on April 10, 2001 with an expected landing on Mars Jan 22, 2002.
- Lander is equipped with an imager to picture the surrounding terrain of the landing site during rocket-assisted descent.
- Lander platform contains instruments and technology experiments designed to provide key insights to decisions regarding human missions to Mars.
- An *in-situ* demonstration test of rocket propellant production was also planned.
- Martial soil properties and surface radiation environment
- **Current Status**: As of 6/00, the Mars Surveyor Lander program was cancelled by NASA. Some consideration is currently being given to a similar Lander design for 2003 or 2005.



Mars Surveyor 2001 Lander- Scientific Payload



Mars Surveyor 2001 Lander- Components



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MSP 2001 Lander Power System

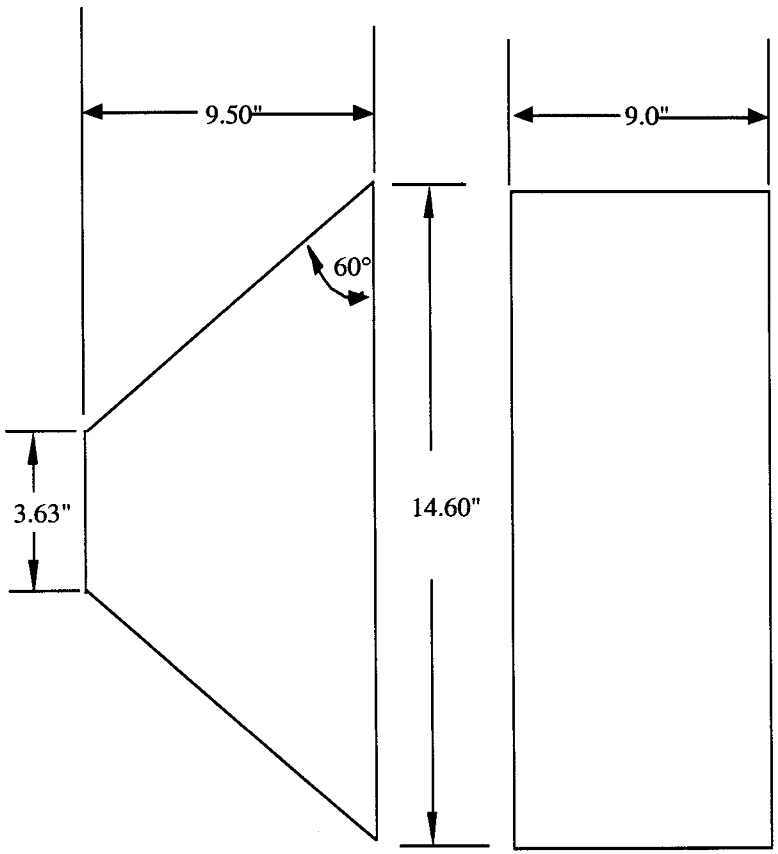
Battery Challenges

- High specific Energy
    - 800 Wh in 7.94 Kg (100 Wh/k
- Low Temperature Performance
    - Op. Temperature : -20 to +40°C
    - Capacity of 24 Ah -20°C at C/5
- Good Cycle Life
    - 200 Cycles @ ~ 70%
- Long Calendar Life
    - Two years of storage (1 year cruise) before battery operation
    - Low temperature performance after storage (final phase of the mission)

MSP 2001 Lander Battery

- Two 25 Ah, 8-Cell Li Ion Batteries (N+1)
- Individual Cell Monitoring and control via Cell Bypass Unit (CBU) to prevent overcharge
- Individual Charge Control Unit (CCU).
- Constant Voltage Charging at - 32.8 Vdc.
- 16 Selectable V/T curves.
- Amp Hour Integration.

Battery Envelope



Lithium-Ion Cells for Mars Surveyor 2001 Lander
JPL Testing Program Objectives

- Assess the viability of using lithium-ion technology for future Aerospace applications.

- Demonstrate the technological readiness of lithium-ion cells for the Mars Surveyor Program 2001 Lander application.

NASA-DOD Interagency Li Ion Program

Objectives

- DEVELOP HIGH SPECIFIC ENERGY AND LONG CYCLE LIFE Li -ION BATTERIES
- ESTABLISH U.S. PRODUCTION SOURCES
- DEMONSTRATE TECHNOLOGY READINESS
  - LANDERS BY 2001
  - ROVERS BY2003
  - GEO MISSIONS BY 2003
  - AVIATION/UAV's BY 2001
  - MILITARY TERRESTRIAL APPLNS's BY 2001
  - LEO MISSIONS BY 2003

Technology Drivers

Mission	Technology Driver
Lander Rover	Low Temperature Operation High rate Pulse Capability
GEO S/C	10-20 Year Operating life Large Capacity cells (50-200 Ah)
LEO PlanetaryS/C	Long Cycle life(30,000) Medium Capacity Cells (50 Ah)
Aircraft	Low temperature Operation High Voltage Batteries (270 V)
UAV	Large Capacity cells (200 Ah) High Voltage Batteries (100V)

Lithium-Ion Cells for Mars Surveyor 2001 Lander
Performance Evaluation Tests

- Cycle Life Performance
  - Room temperature cycle life (23° +/- 2°C)
  - Low temperature cycle life (-20°C)
  - High temperature cycling (40°C)
  - Variable temperature cycling
- Electrical Performance Characterization
  - Range of charge and discharge rates (C/2, C/3.3, C/5 and C/10)
  - Range of temperatures (-30, -20, 0, 23, 40°C)
  - Pulse capability (40 and 60A)
  - Impedance measurements
- Storage Characteristics
  - 2 Month OCV storage test (0 and 40°C, 50 and 100% SOC)
  - 10 Month OCV storage test (0 and 40°C, 50 and 100% SOC)
  - 10 Month Buss storage tests
- Mission Simulation Profile Test
  - EDL Pulse Test
  - Mission Simulation Cycle Life Testing

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Lithium-Ion Cells for the Mars Surveyor 2001 Lander Cycle Life Performance Tests

Requirement : Deliver > 200 cycles on surface of Mars

- 100% DOD cycling (3.0-4.1V, C/5-C/10)
- Wide temperature range (-20°C to 40°C)
- At end of life should deliver 25 Ah

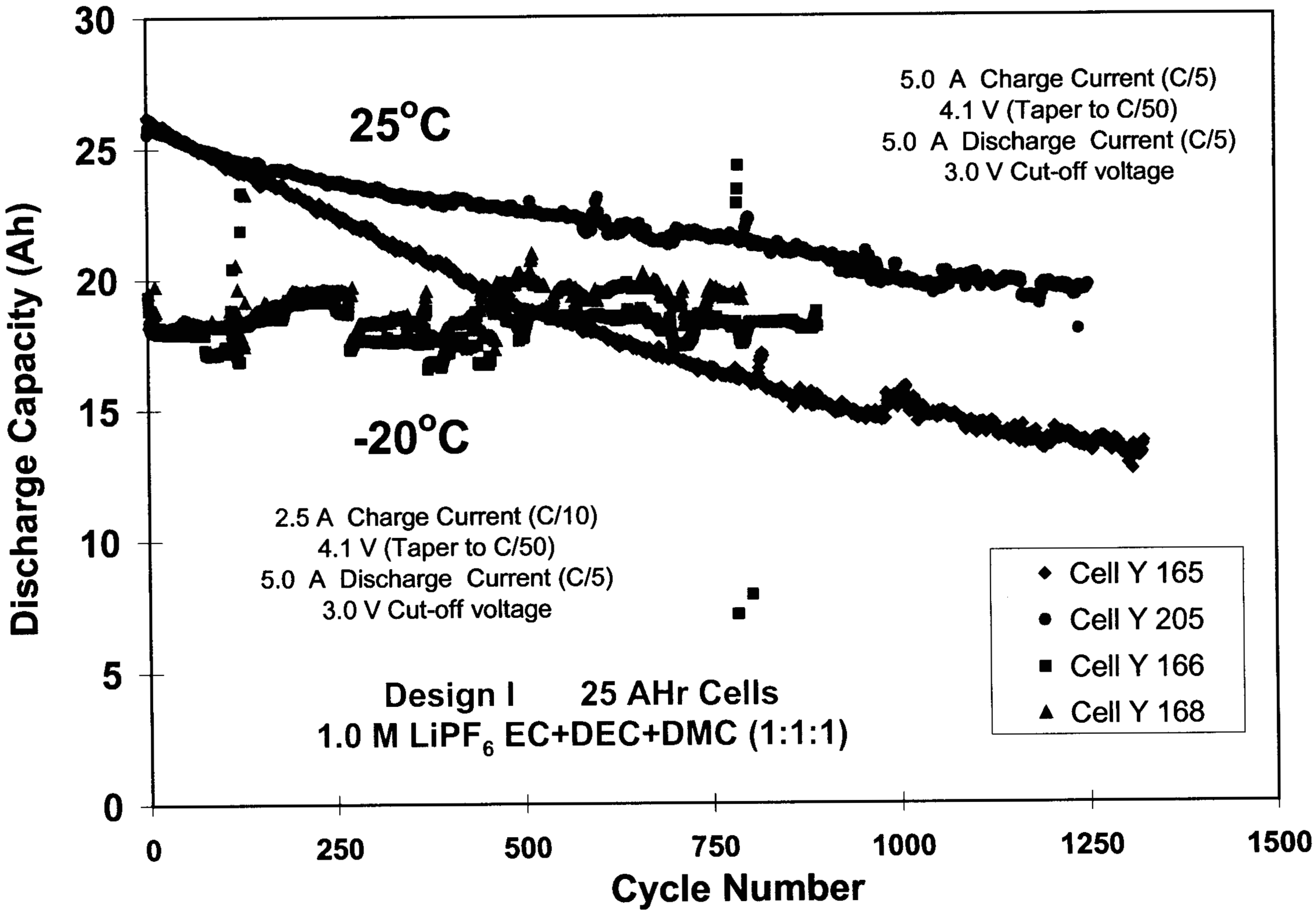
Approach:

100 % DOD cycling @ 23°C (C/5 charge, C/5 discharge)
100 % DOD cycling @ -20°C (C/10 charge, C/5 discharge.)
100 % DOD cycling @ 40°C (C/5 charge, C/5 discharge)
Variable temperature cycling (temperature extremes)
Mission simulation cycling

Possible Evaluation Criteria:

Initial capacity (must exceed 25 Ah)
Capacity after 200 cycles (Ah)
Capacity fade rates
Capacity delivered over range of temperatures

Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications Cycle Life Performance at Different Temperatures



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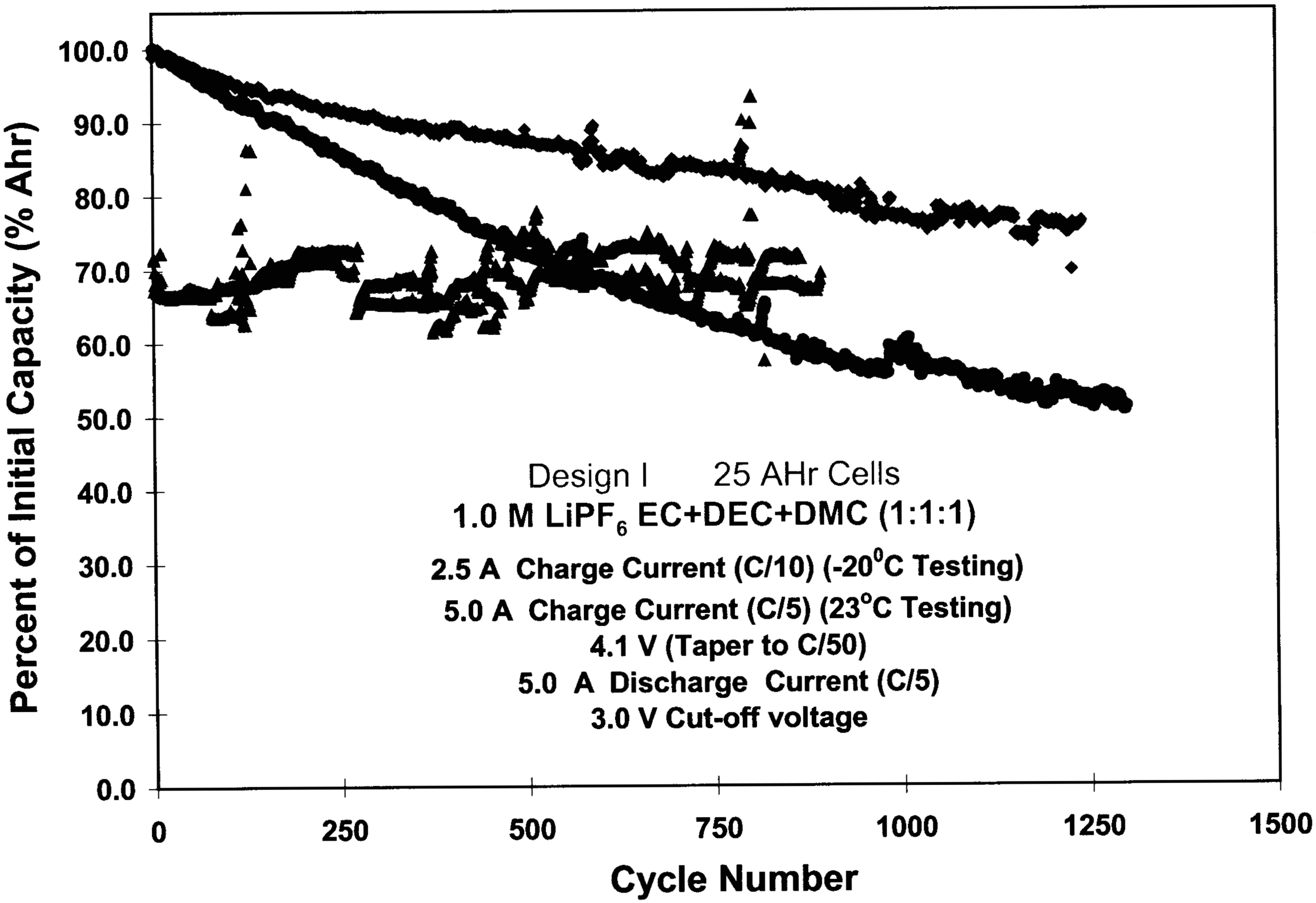
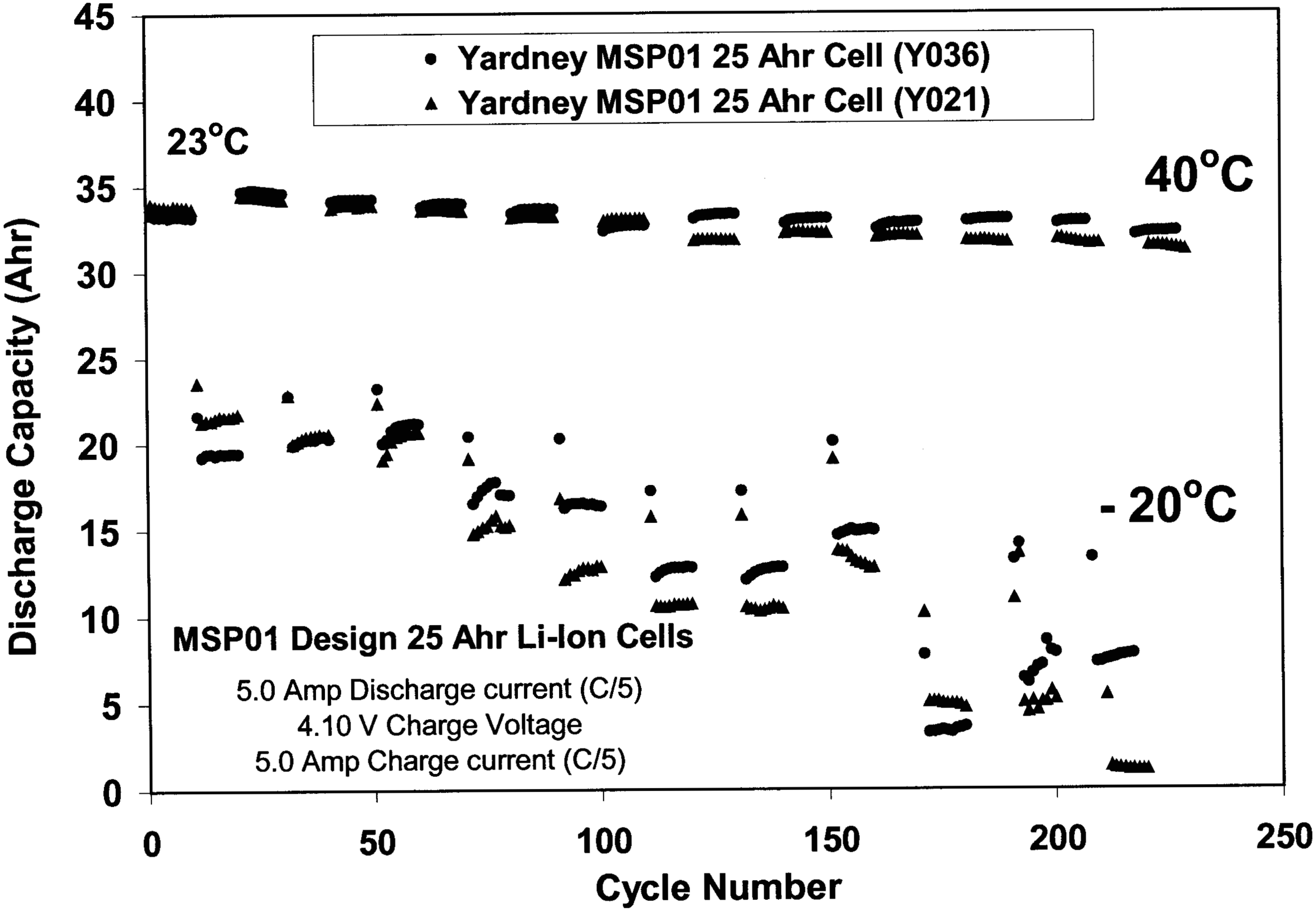
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
Cycle Life Performance at Different Temperatures



Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
MSP01 Design Cells - Variable Temperature Cycling
Discharge Capacity



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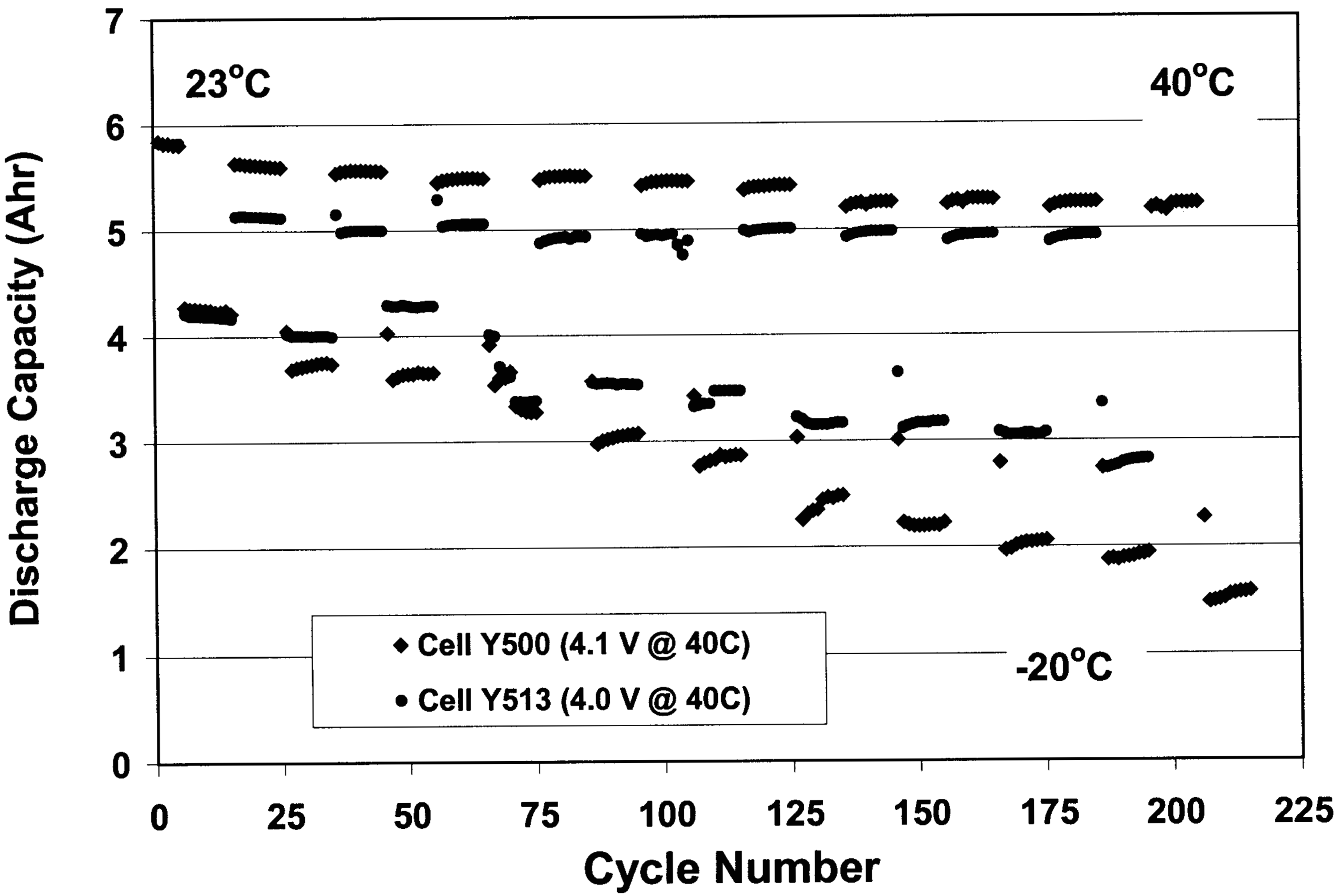
Yardney Lithium-Ion Cells for Future Mars Lander /Rover Applications
Rover 5 Ahr Cell Design - Variable Temperature Cycling
Discharge Capacity



Lithium-Ion Cells for the Mars Surveyor 2001 Lander
Low Temperature Performance Evaluation

Requirement :

- Provide 25 Ah over wide range of temperatures (-20°C to 40°C)
- Provide 25 Ah at C/2 rate - C/10 rate
- Should be capable of meeting mission profile

Approach :

Rate characterization at various temperatures (-20, 0, 20 and 40°C)
Range of charge and discharge rates (C/2, C/3.3./C/5 and C/10)

Possible Evaluation Criteria :

Low temperature discharge capacity (at - 20°C)
Low temperature charge characteristics
Capacity delivered over range of temperatures
Discharge energy (Wh/Kg)
Watt-hour efficiency (round-trip efficiency)
Heat generation
Effect of cell history upon rate capability

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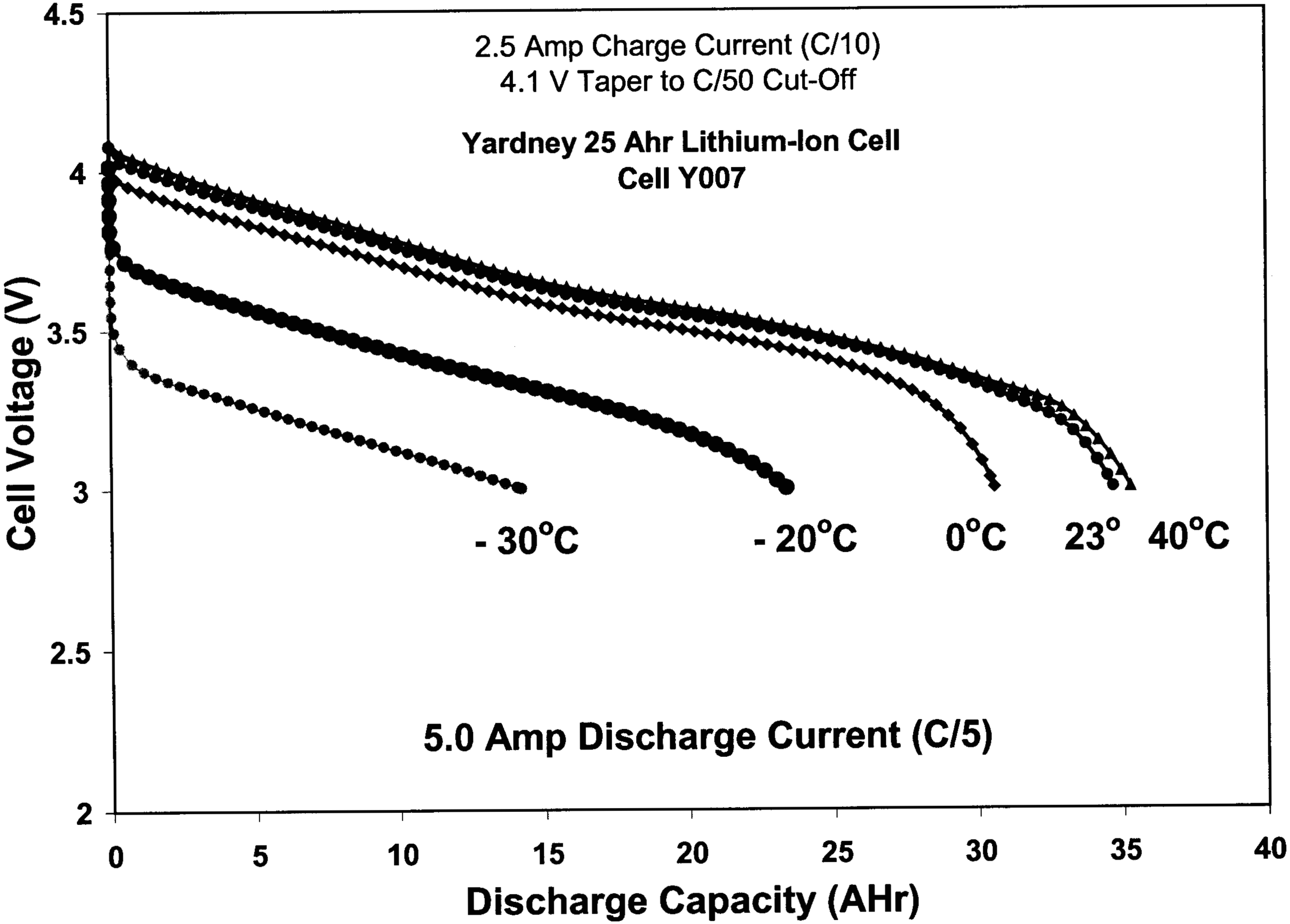
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
MSP01 Design Cells - Discharge Characteristics at Different Temperatures



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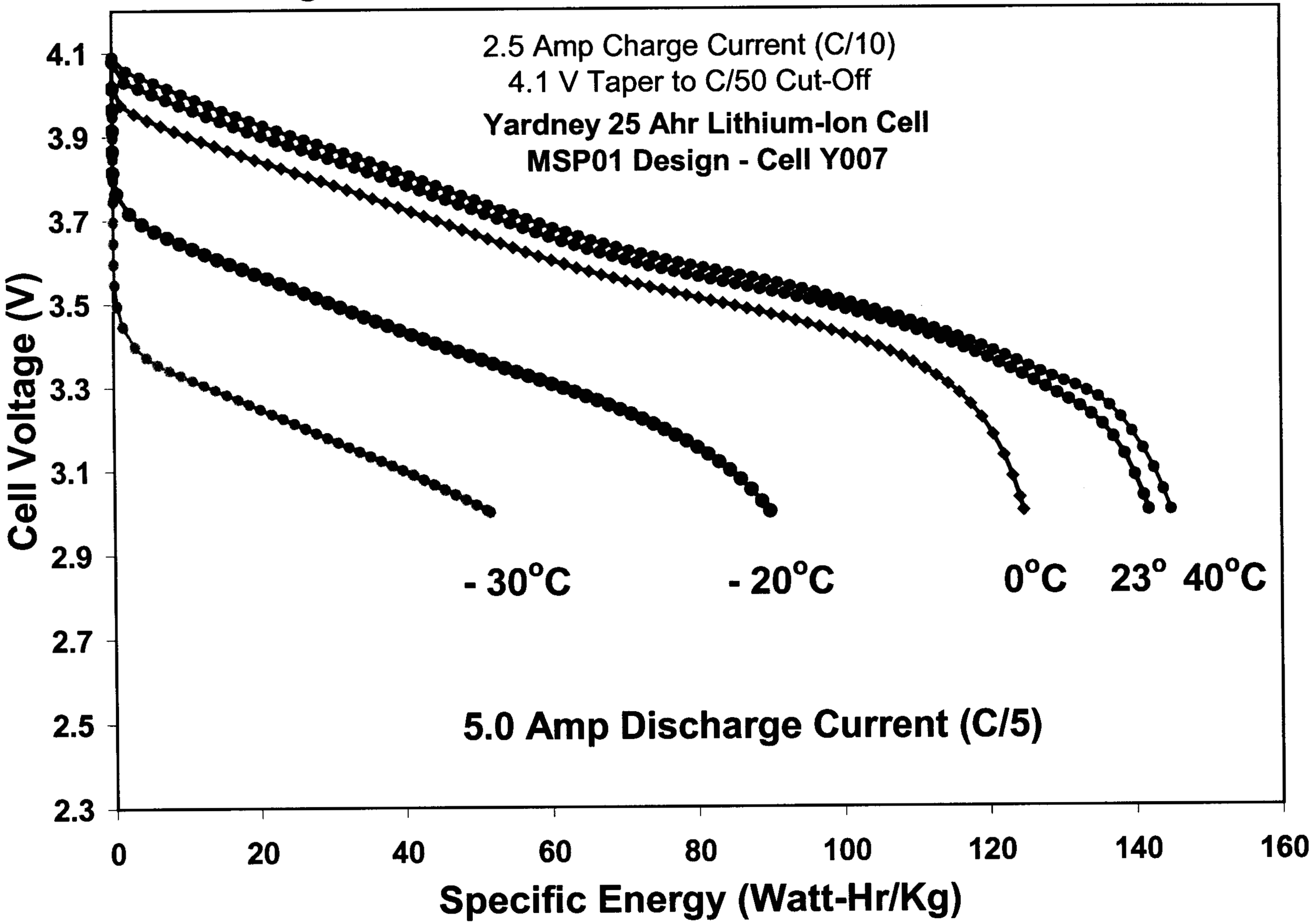
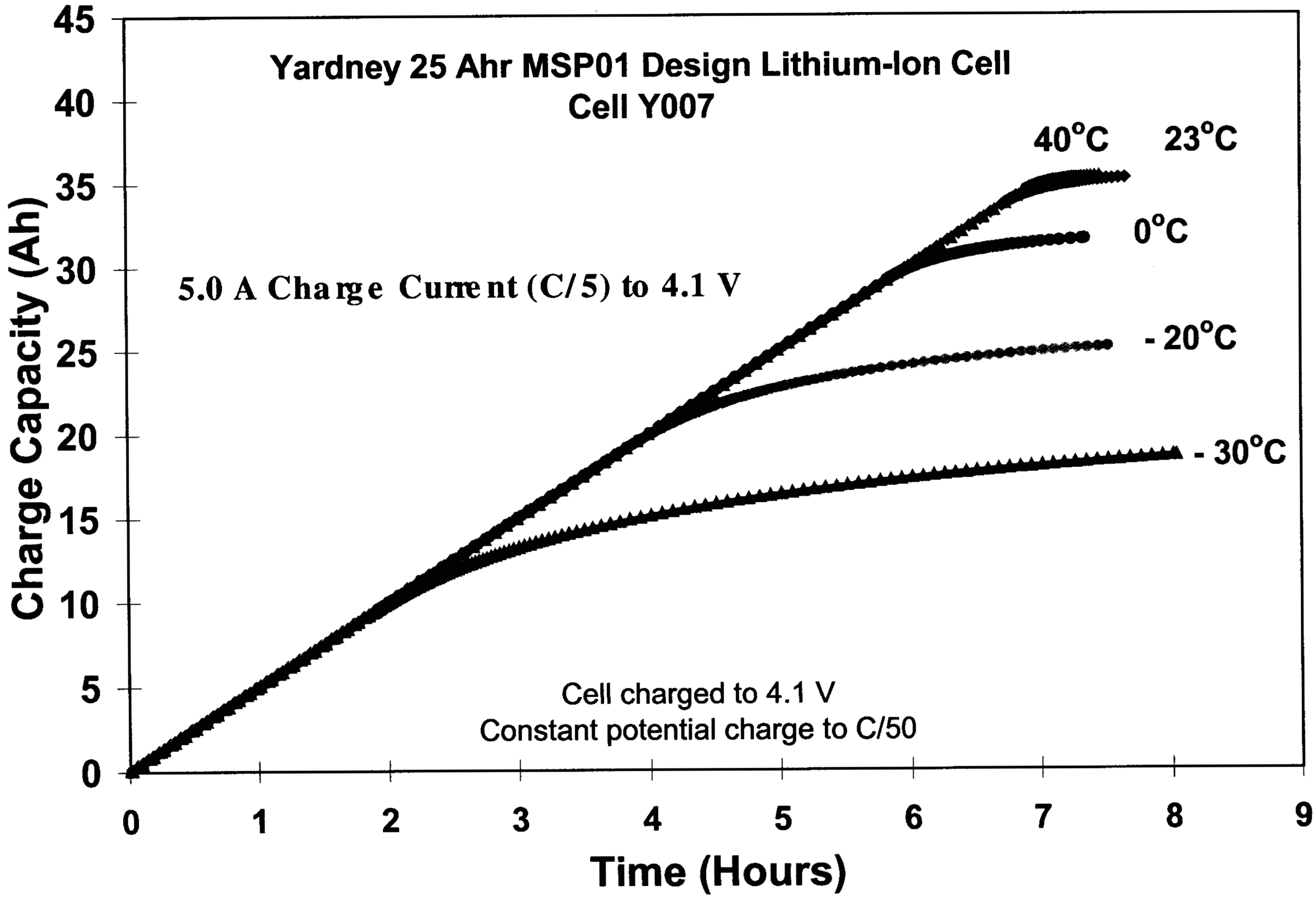
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
MSP01 Design Cells - Discharge Energy at Different Temperatures



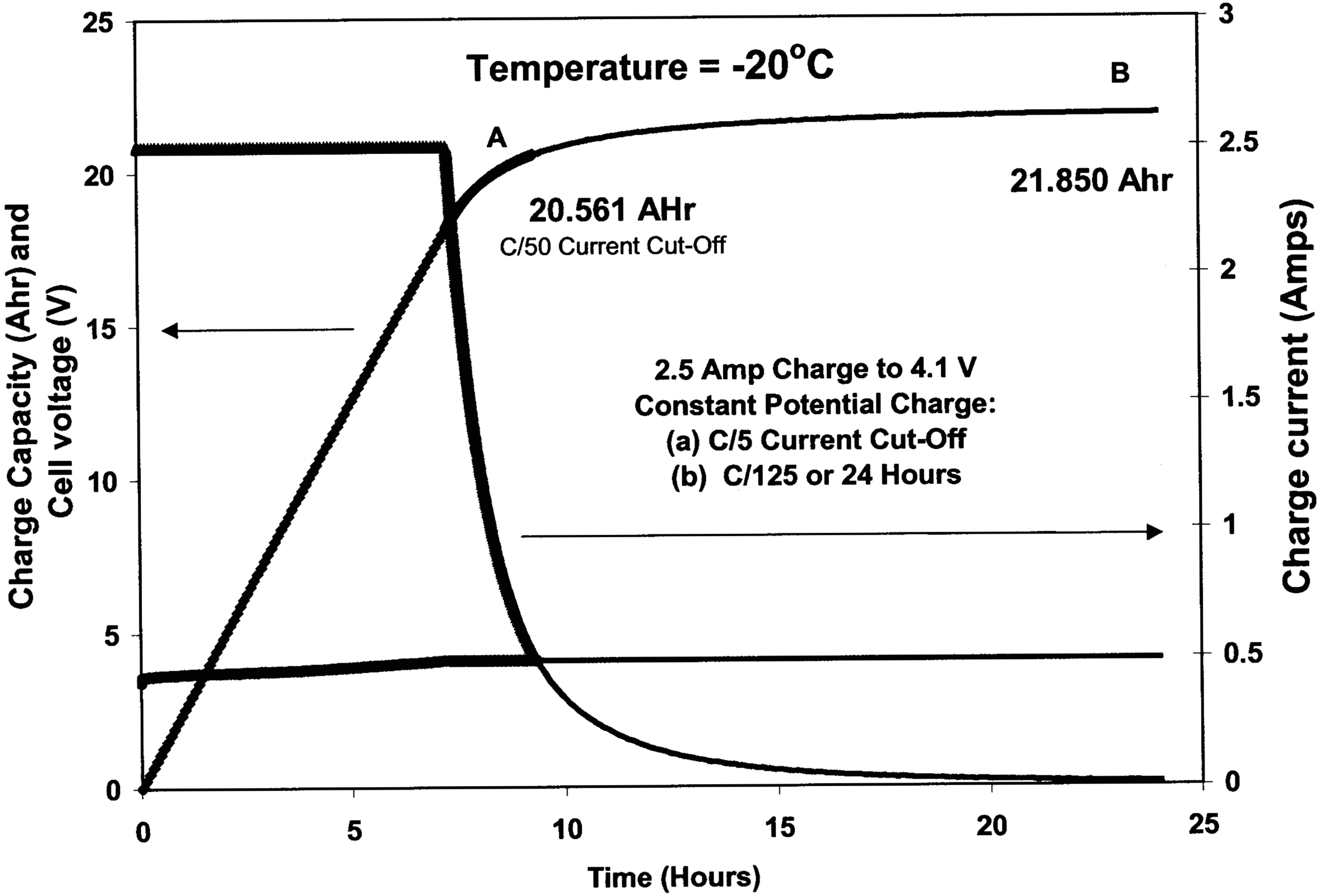
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

MSP01 Design Cells - Charge Characteristics at Different Temperatures



Yardney Lithium-Ion Cells for Mars Lander Applications

Charge Characteristics at Low Temp-Effect of Taper Charge Current Cut-Off



Lithium-Ion Cells for Mars Surveyor 2001 Lander
Capacity Retention Characterization Tests

Requirement :

- Should be capable of meeting all other requirements after prolonged storage period (>10 months)

Approach :

- Identify optimum storage conditions
- Quantify performance degradation due to storage
    - 2 Month OCV storage test (0 and 40°C, 50 and 100% SOC)
    - 10 Month OCV storage test (0 and 40°C, 50 and 100% SOC)
    - 10 Month buss storage (70% SOC at 10°C)
    - 10 Month buss storage (different SOCs and variable temperature)
    - Accelerated storage test: (at different SOC (50, 70,100% SOC), temperatures (0, 25, 40, 50°C), and storage conditions.

Possible Evaluation Criteria :

- Self-discharge of stored capacity
- Permanent loss of reversible capacity
- Impact upon low temperature performance

Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

Storage Characteristics of Gen I Cells- Results of 10 Month Storage Test

[redacted]

	Initial	[redacted]														
Cell Number and Storage Mode	Initial Capacity (After Cond.)	Capacity Prior To Storage (Ah)	Stored Capacity	Cell Voltage after 10 Month Storage	Capacity After Storage (Ah) 1st Disch.	Capacity After Storage (Ah) 5th Disch.	Capacity Loss (% of stored capacity)	Rever. Capacity (%)	Capacity Prior To Storage (Ah)	Stored Capacity	Cell Voltage after 10 Month Storage	Capacity After Storage (Ah) 1st Disch.	Capacity After Storage (Ah) 5th Disch.	Capacity Loss (% of stored capacity)	Rever. Capacity (%)	Total Reversible Capacity After 12 Months (% from Initial)
Y151 (0°C and 50 % SOC)	27.879	27.609	14.000	2.565 V	0.000	27.327	100	98.976	26.972	14.000	0.578 V	0.000	26.786	100	99.312	96.079
Y152 (40°C and 50 % SOC)	28.749	28.021	14.000	3.308 V	1.968	27.479	85.943	98.065	27.918	14.000	0.482 V	0.000	25.595	100	91.679	89.029
Y178 (0°C and 100 % SOC)	25.475	25.471	25.487	3.982 V	23.114	24.781	9.310	97.289	24.607	24.623	3.762 V	16.996	24.296	30.975	98.739	95.371
Y201 (40°C and 100 % SOC)	25.674	25.670	25.584	3.834 V	19.611	25.156	23.349	97.998	23.912	23.807	3.608 V	10.309	22.727	56.699	95.045	88.524

Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

Storage Characteristics of Gen I Cells- Results of 10 Month Storage Test

Cell Number and Storage Mode	Initial Capacity	Capacity Prior To Storage (Ah)	Stored Capacity	Cell Voltage after 10 Month Storage	Capacity After Storage (Ah) 1st Discharge	Capacity After Storage (Ah) 5th Discharge	Capacity Loss (% of stored capacity)	Rever. Capacity (%)	Total Reversible Capacity (% from Initial)	1st Discharge at 20°C (5 Amps = C/5)	% of Initial Capacity	2nd Discharge at - 20°C (5 Amps = C/5)	% of Initial Capacity
Y151 (0°C and 50 % SOC)	27.879	26.972	14.000	0.578 V	0	26.7859	100	99.31	96.079	17.276	61.966	16.047	57.558
Y152 (40°C and 50 % SOC)	28.749	27.918	14.000	0.482 V	0	25.5949	100	91.68	89.029	18.935	65.864	16.961	58.996
Y178 (0°C and 100 % SOC)	25.475	24.607	24.623	3.762 V	16.996	24.2963	30.97	98.74	95.371	12.995	51.010	11.031	43.301
Y201 (40°C and 100 % SOC)	25.674	23.912	23.807	3.608 V	10.309	22.7273	56.70	95.05	88.524	11.400	44.403	8.558	33.334

Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

Storage Characteristics of MSP01 Design Cells- Results of 10 Month Storage Test

Cells Stored on the Buss at 10°C (70% SOC)

		[redacted]							
	Last Discharge Prior to Storage (Ahr)	1st Discharge After Storage (Ahr) 23°C	2nd Discharge After Storage (Ahr) 23°C	% of Initial Capacity (Reversible Capacity)	Permanent Capacity Loss (%)	1st Discharge After Storage (Ahr) 23°C	2nd Discharge After Storage (Ahr) 23°C	% of Initial Capacity (Reversible Capacity)	Permanent Capacity Loss (%)
[redacted]	33.804	26.034	33.523	99.169	0.831	25.6252	32.9636	97.515	2.485
	33.962	25.959	33.534	98.738	1.262	29.059	32.266	95.006	4.994
	34.153	25.445	32.788	96.005	3.995	25.639	32.999	96.622	3.378
	33.727	25.922	33.460	99.210	0.790	25.478	32.917	97.599	2.401

Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

Storage Characteristics of MSP01 Design Cells- Results of 10 Month Storage Test

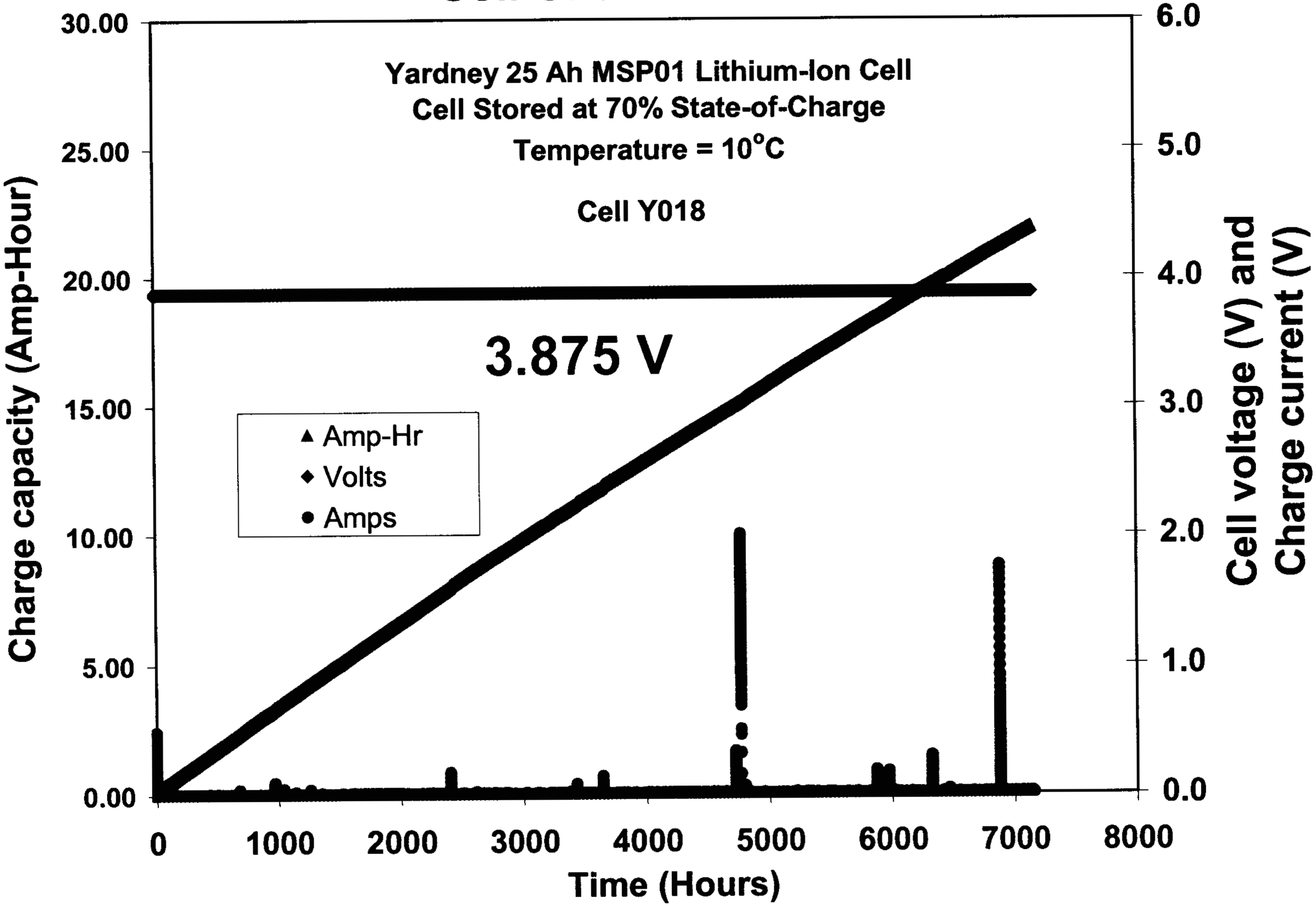
Cells Stored on the Buss at 10°C (70% SOC)

Impact Upon the Low Temperature Performance

		[redacted]				Low Temperature Performance After Storage Period			
	Last Discharge Prior to Storage (Ahr)	1st Discharge After Storage (Ahr) 23°C	2nd Discharge After Storage (Ahr) 23°C	% of Initial Capacity (Reversible Capacity)	Permanent Capacity Loss (%)	1st Discharge (Ahr) -20°C	% of Initial Room Temp Capacity	2nd Discharge (Ahr) -20°C	% of Initial Room Temp Capacity
[redacted]	33.804	25.62524	32.9636	97.515	2.485	22.466	66.46	19.537	57.79
	33.962	29.059	32.266	95.006	4.994	22.099	65.07	19.437	57.23
	34.153	25.639	32.999	96.622	3.378	22.224	65.07	19.299	56.51
	33.727	25.478	32.917	97.599	2.401	22.397	66.41	19.647	58.25

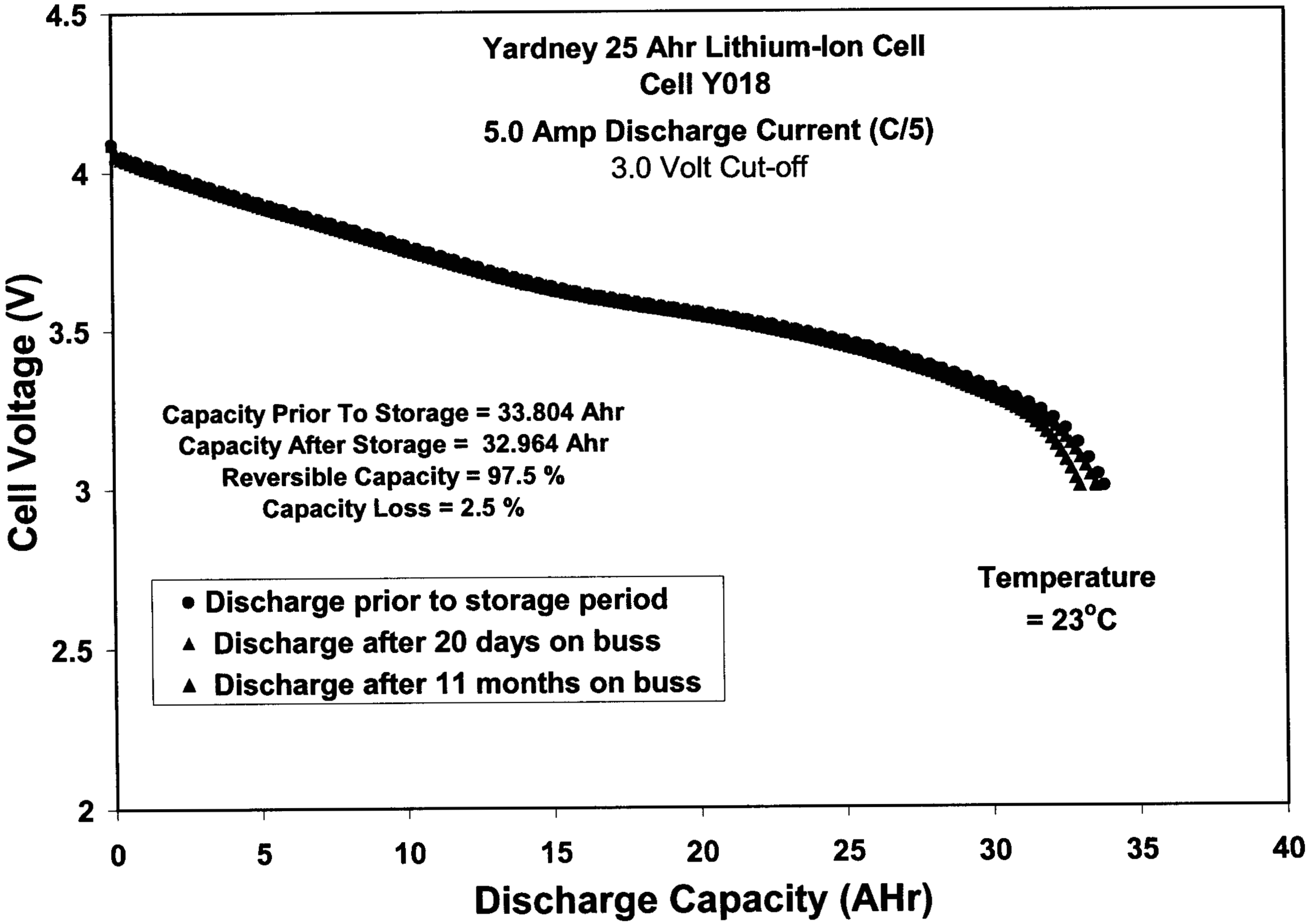
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications MSP01 Design Cells - Storage of the Cells on the Buss at 10°C

Cell Characteristics



Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

Storage Characteristics of MSP01 Design Cells- Results of 11 Month Storage Test
Cell Stored on the Buss at 10°C (70% SOC)



Lithium-Ion Cells for the Mars Surveyor 2001 Lander EDL and Mission Simulation Tests

Requirement :

- Meet entry, descent and landing (EDL) power requirements
- Successfully cycle cells on the surface of Mars (temperature range of -20°C to 40°C)

Approach :

Store cells for > 10 months to simulate cruise period

Test cells under EDL profile at 0°C

Cycle cells under varying temperature profile

- 12 Hour charge period (-20 to 40°C)
- 12 Hour discharge period (40 to -20°C)
- Change temperature range to model seasons

Possible Evaluation Criteria:

Discharge voltage on EDL profile (>3.0V each cell)

End of discharge voltage on cycling test (>3.0V each cell)

Cell variance

Capacity fade upon cycling

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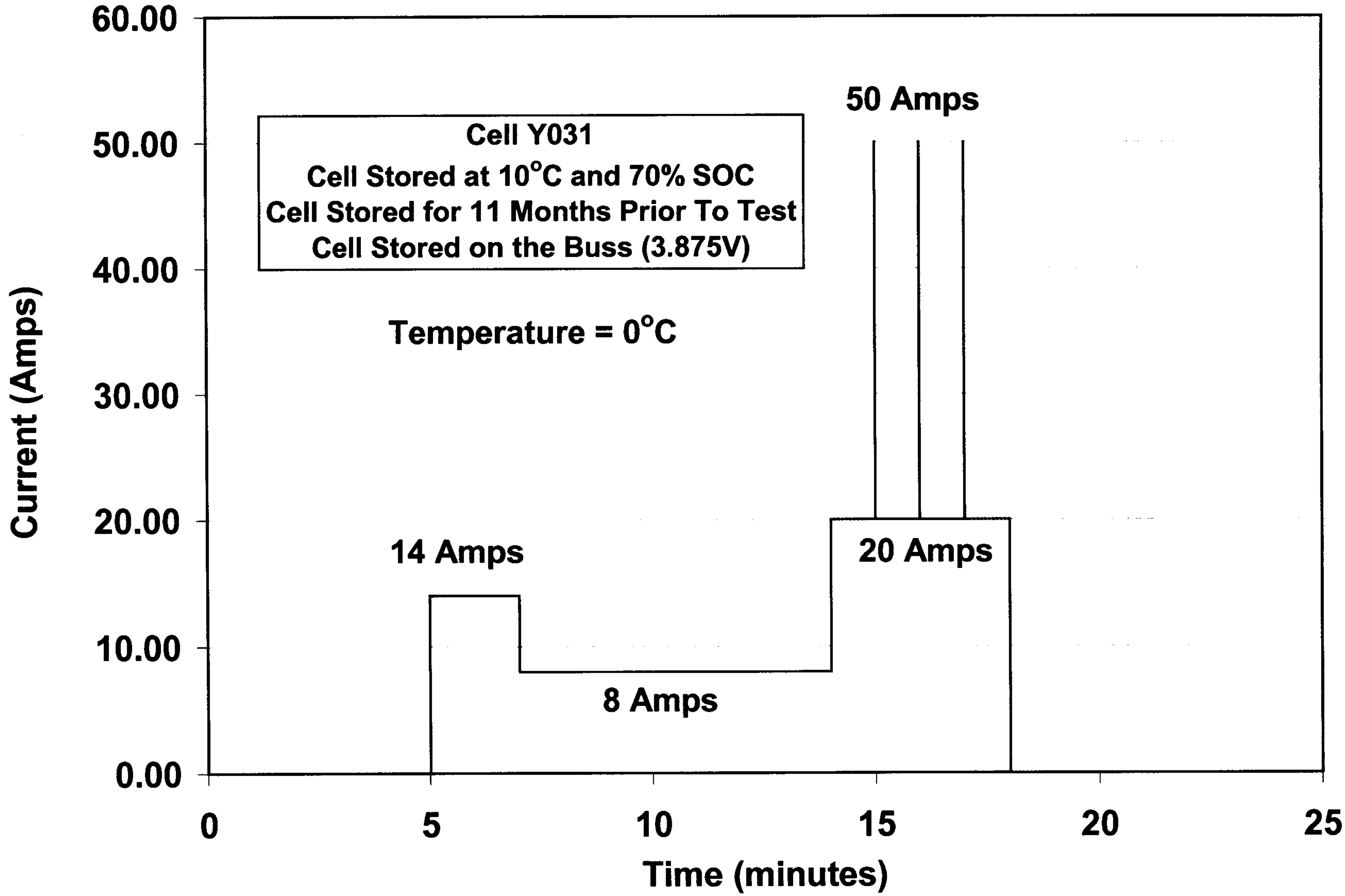
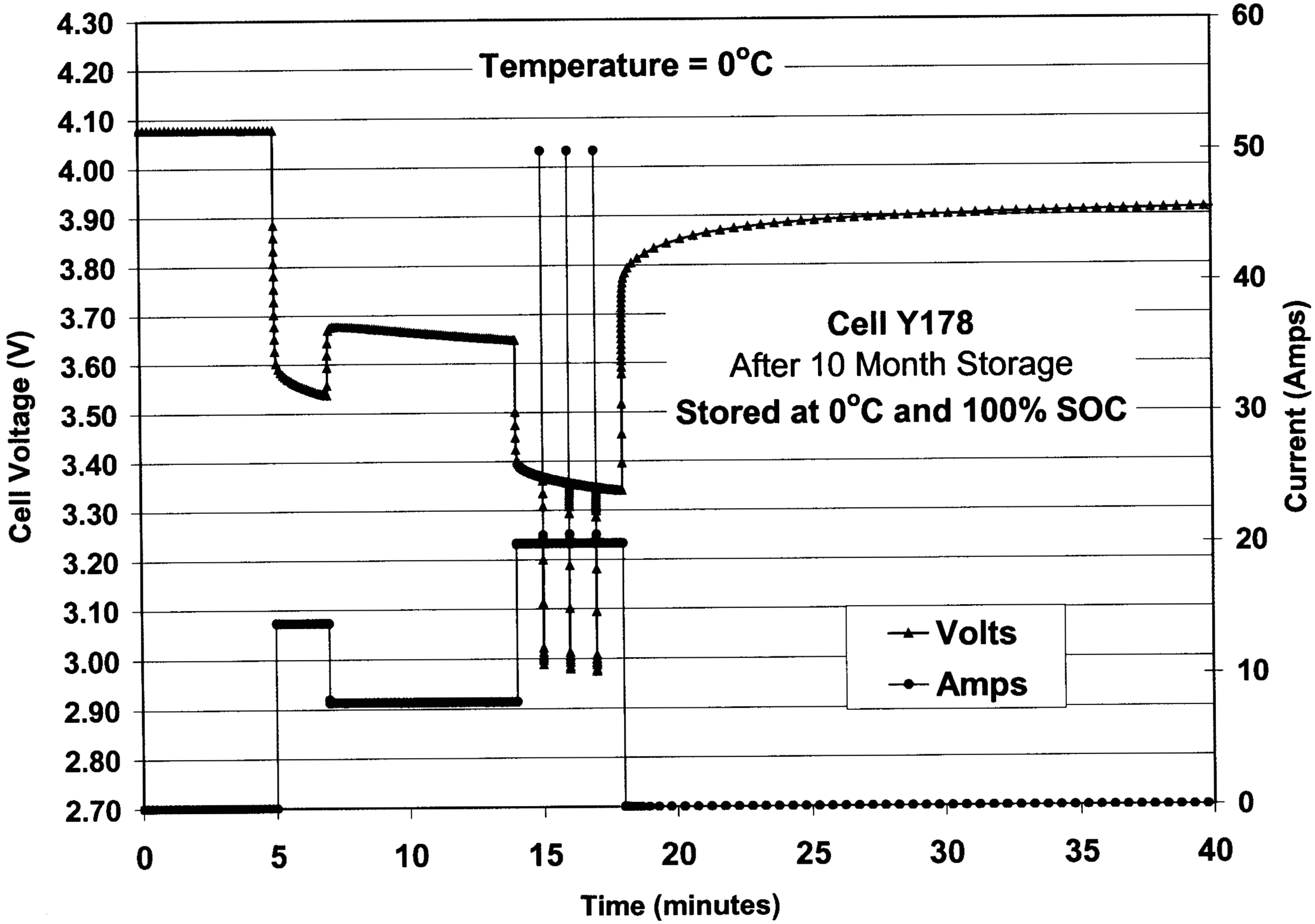
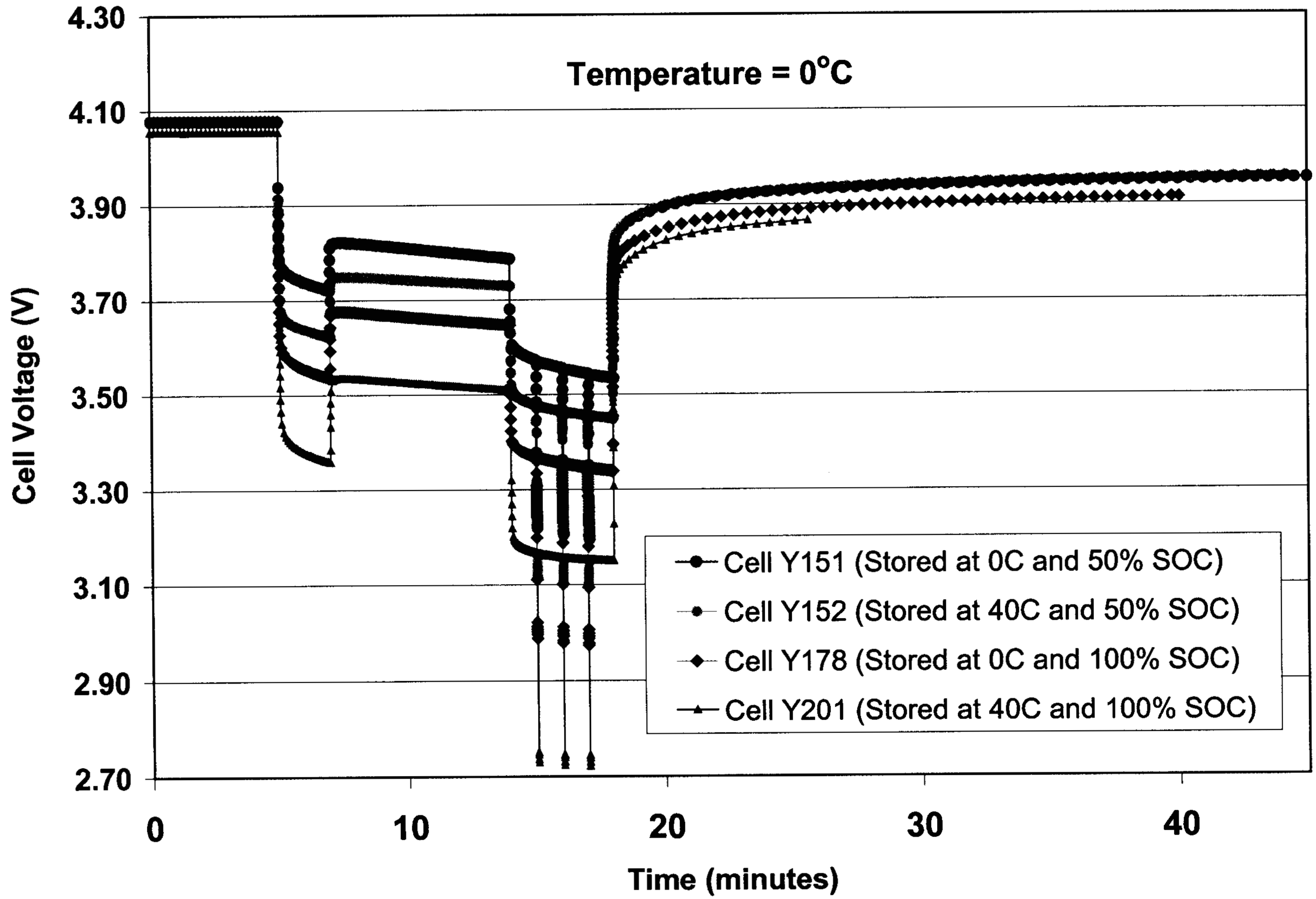
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
EDL Discharge Profile Simulation



Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
EDL Discharge Profile Simulation



Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
EDL Discharge Profile Simulation of Gen I Cells



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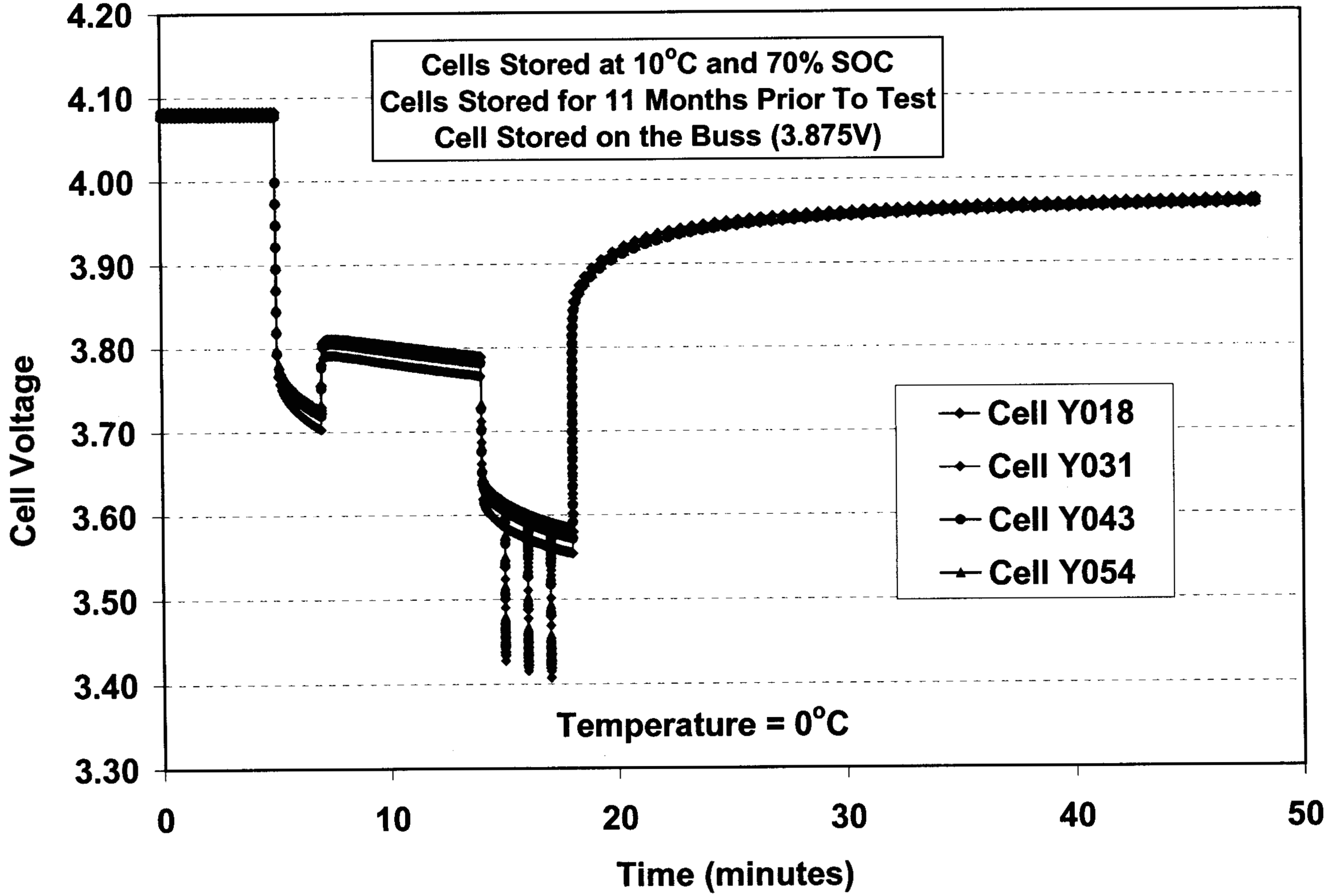
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
EDL Discharge Profile Simulation of MSP01 Design Cells



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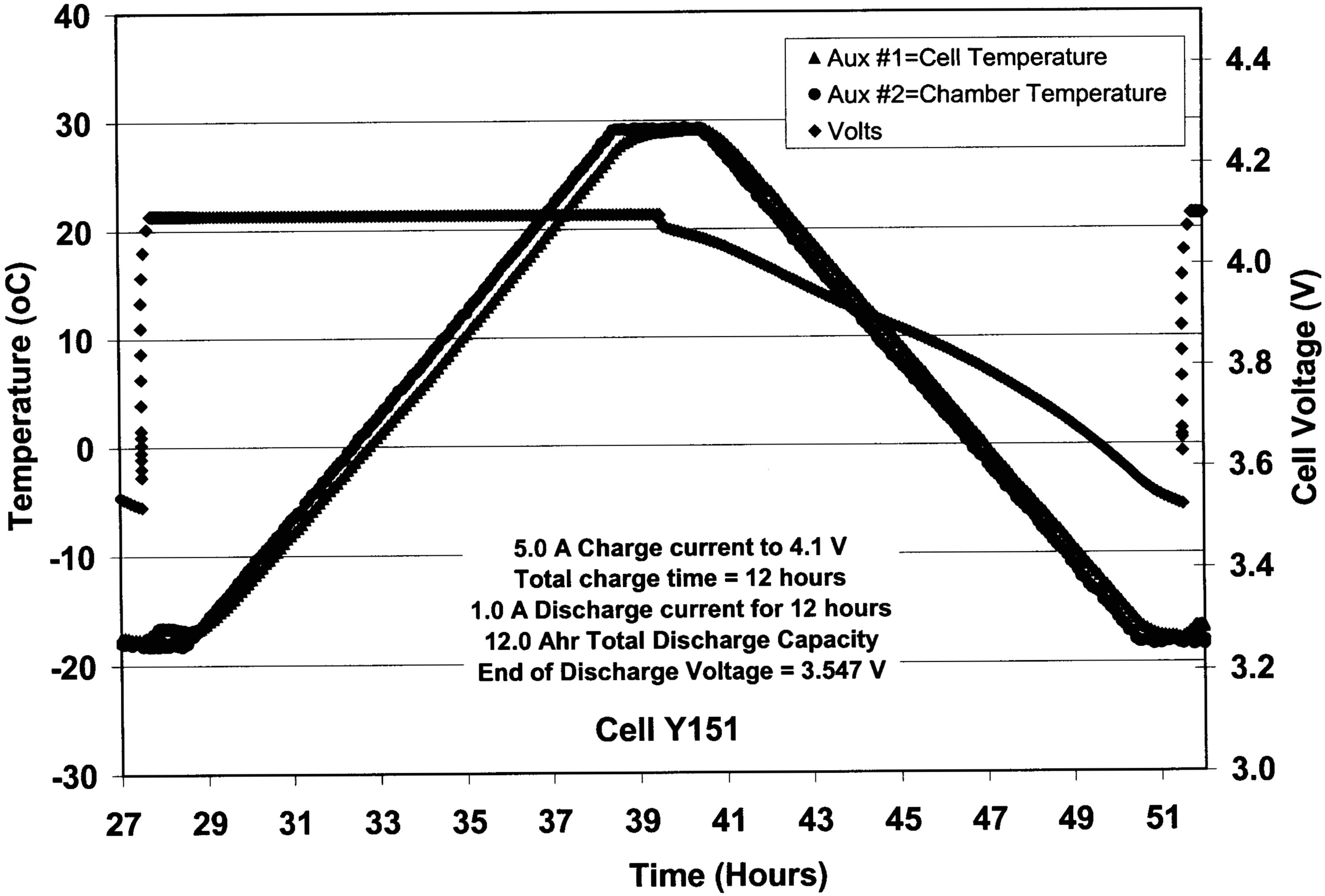
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications Mission Simulation Profile: Second Temperature Range



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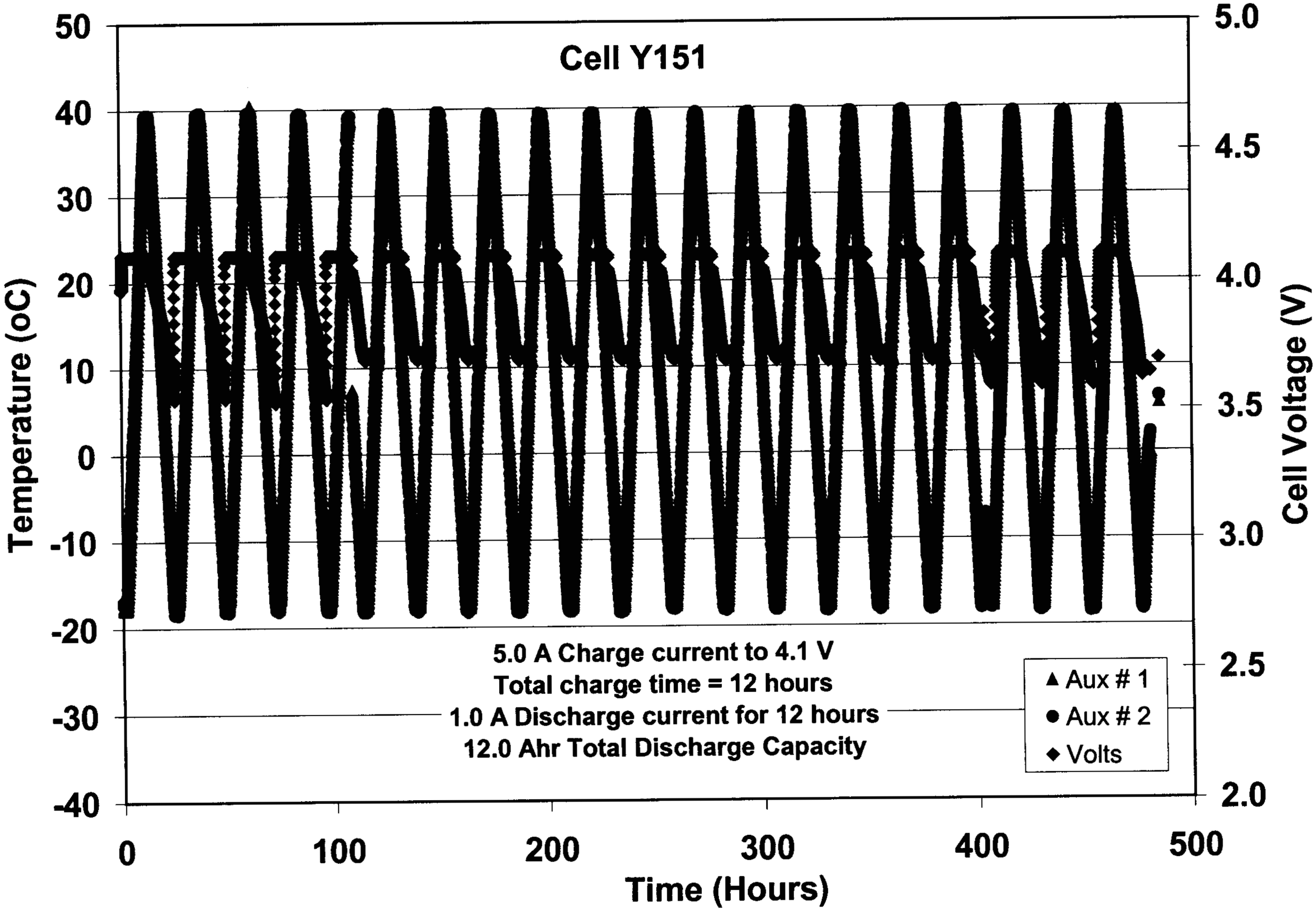
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
Mission Simulation Profile: First Temperature Range



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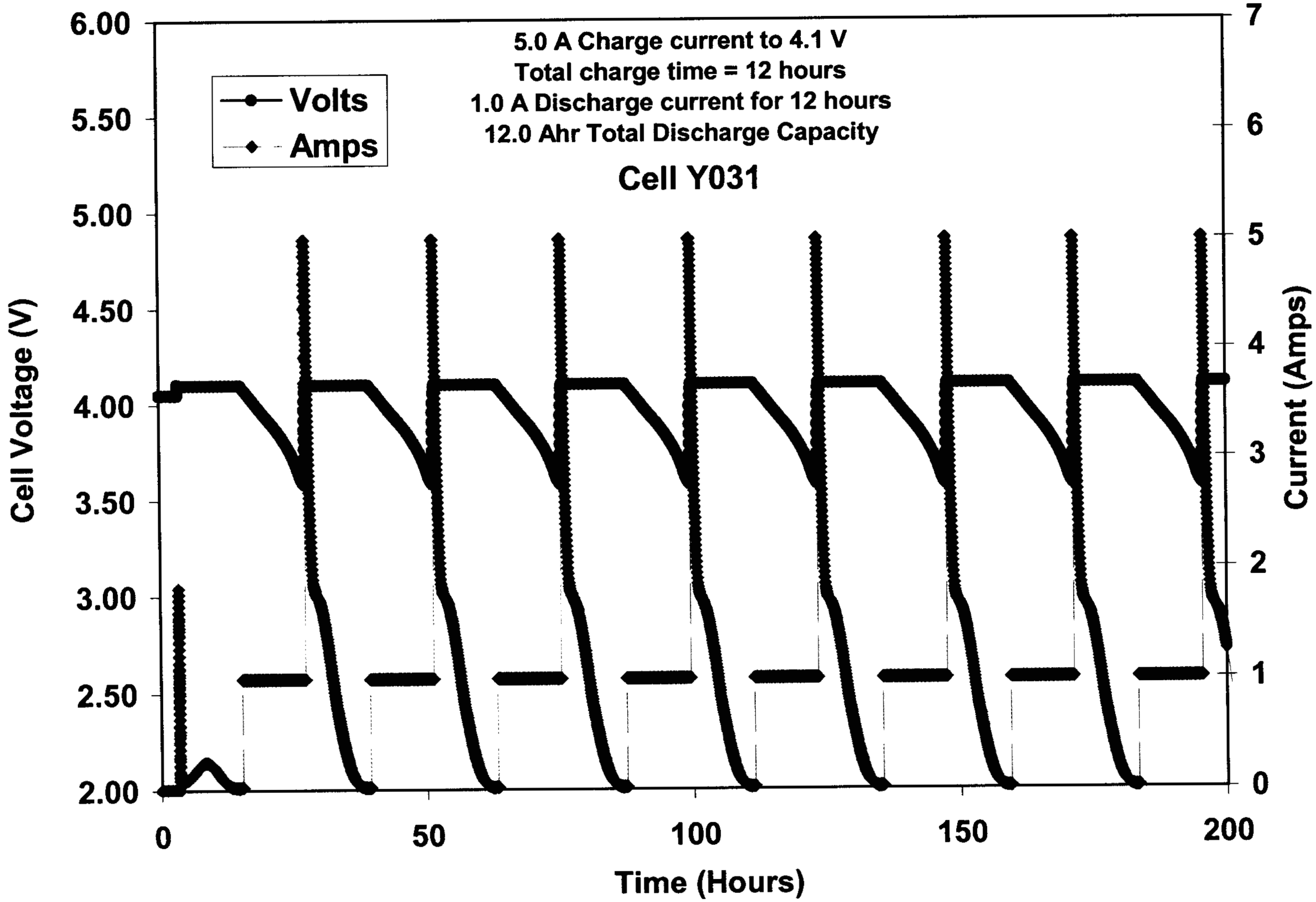
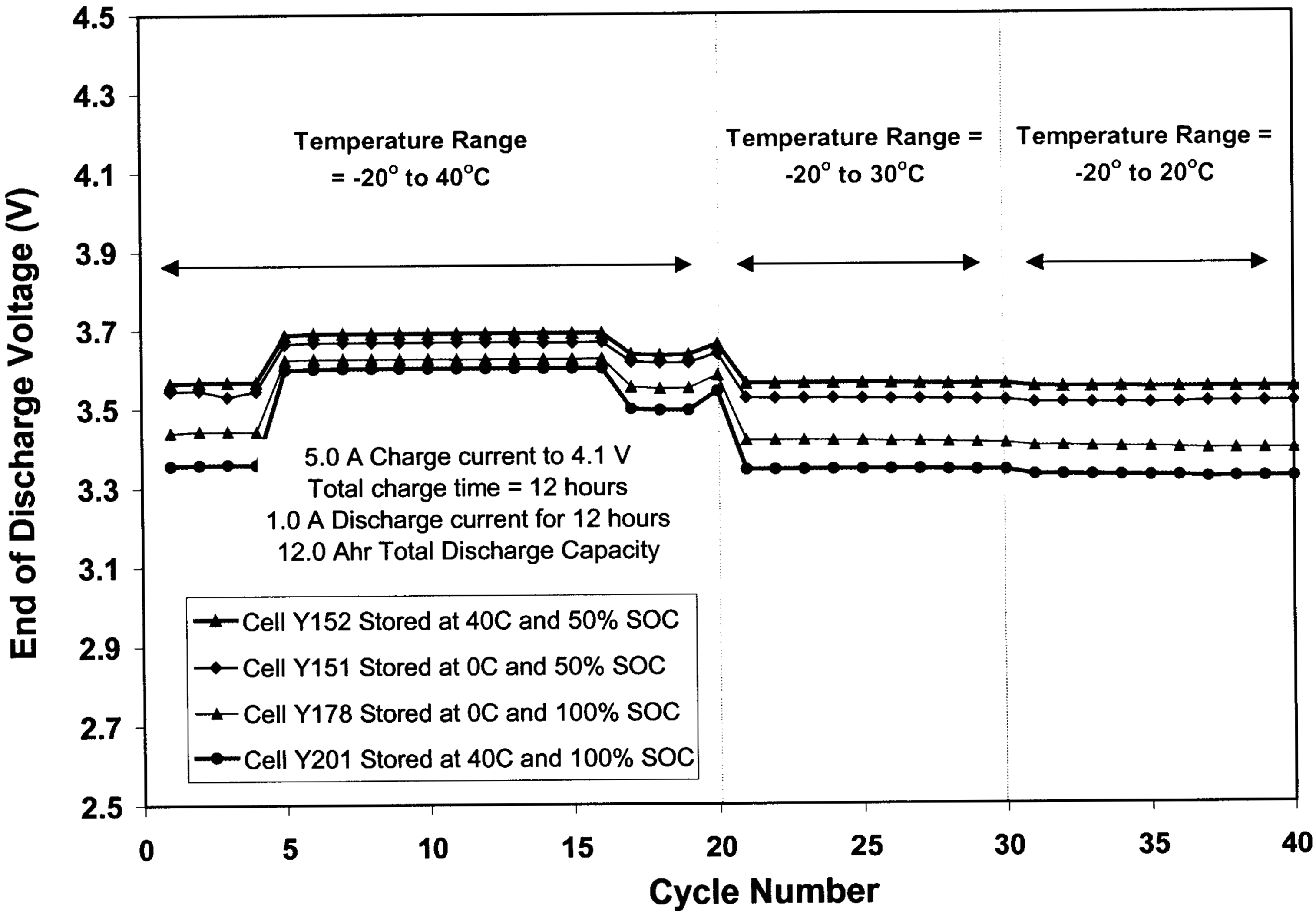
Yardney MSP01 Design Lithium-Ion Cells for Mars Lander Applications
Mission Simulation Profile



Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
Mission Simulation Profile: End of Discharge Voltage



SUMMARY

- ***Li Ion cells meet the MSP 2001 Lander mission requirements:***
  - ***Cycle Life Performance***
    - Room Temperature = Excellent (>90% @ 200 cycles)
    - Low Temperature (-20) = Sufficient
    - High Temperature (40°C) = Sufficient (>70% @ 200 cycles)
  - ***Discharge Rate Capability at Various Temperatures***
    - Room Temperature = Excellent
    - Low Temperature (-20°C) = Sufficient (~ 24 Ah @ C/5 rate)
    - High Temperature (40°C) = Excellent
  - ***Storage Characteristics***
    - Demonstrated minimal reversible capacity loss (2 months)
    - Identified temperature as most crucial storage parameter
    - Demonstrated efficacy of storage "on the buss"
  - ***Mission Simulation Testing***
    - MSPO1 design cells effective meet EDL pulse requirements (> 3.0V)
    - Cells successfully cycled under mission simulation conditions (-20°C to +40°C)

Acknowledgments

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